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PATH PLANNING AND ADAPTIVE CONTROL OF A MULTI-AXIS SURFACE FINISHING ROBOT

Submitted by Peter John GOODCHILD

for the degree of Ph.D.
of the University of Bath
1986

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SUMMARY

The current use of robotic devices in surface finishing has been limited to the low technology applications. To progress from the relatively simple task of coarse fettling and deburring, to the controlled surface finishing of more complex shapes will require more sophisticated robot devices. These will be capable of adaptive control for the machining operation, in-process inspection, path planning and decision making.

The thesis describes the design and development of a novel robot system to grind the surface of complex geometry die castings, that are used in the manufacture of a range of bath room fittings. The system is designed to mimic the tenacity and flexibility of the human polishing action, whilst maintaining the overall blended surface geometry.

The robot is based on a modular construction incorporating several independently controllable linear and revolute axes, that are driven by stepper motors. The grinding head uses a continuous abrasive belt configured to run over suitable form wheels. Three microprocessors are used to control the robot system.

The path of the head is derived automatically from a mathematical model of a master component, and knowledge of the robot kinematics. This is then modified in real time to provide adaptive control of the metal removal process, based upon a novel measuring of grinding intensity. The system also incorporates a machine vision system to identify the position of surface defects. The information is then used by the master controller to selectively machine the surface, and remove persistent defects.

ACKNOWLEDGEMENTS

The work described in this thesis is the conclusion of a major research project undertaken by the Manufacturing Group, School of Engineering. The project was concerned with the development of a robotic polishing device suitable for complex geometry components, and was suppported by the Science and Engineering Research Council and Walker Crosweller Ltd.

The original contribution made by the author is the development of a measuring and adaptive control system for the grinding process, incorporated with an optimum geometry abrasive head, and the machining strategies which maintain the integrity of the component geometry, which allowed the complete system to be commissioned.

However in order to put the authors work in context, it has been necessary to include within the introductory chapters work perfomred by other members of the research team. In particular the work of Y.C Choong, S. Jenkins and W. Wright and the original ideas of the system developed by Dr. D Graham and Dr. J.R. Woodwark.

The author has been most grateful to the guidance of Dr. Graham both during the project and through the writing of this thesis. I also wish to thank all of the staff, technicians and post-graduates of the Manufacturing Group who have contributed directly or indirectly to this project.

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1. INTRODUCTION

When a company considers the introduction of automation and robotics within its production system, the project must be both technically feasible and commercially sound. The only sensible exception to these simple rules occurs when the economic viability is of secondary importance to safety, and where there is a need for automated systems within a potentially hazadous environment unsuitable for human activity.

Economic viability will usually be established by considering such factors as the reduction in direct labour, less work-in-progress, improved through-put-time, increased or consistent quality, or as an essential item within a computerised integrated manufacturing facility. Technical feasibility relates to an assessment of the required speed, accuracy and complexity of the action, the degree of order within the robot environment, and the need for computer path planning and decision making capabilities.

A brief examination of the current market place shows that robots are installed predominatly in low technology applications which have obvious cost benefits, e.g. paint spraying, spot welding and general material handling. As the technology has developed, especially with regard to external sensory devices, control systems, and programming techniques, more sophisticated economically viable systems are being introduced, for example in component assembly.

The system described within this thesis is interesting in that the apparent mundane task of surface finishing a range of bathroom taps and shower fittings, has required the development of an advanced robot system with both sensory perception and decision making capabilities. The work represents a significant advance in the development of techniques for the often neglected production problem of component surface finishing.

It is hoped that readers, with different robotic interests from the main subject matter of automating surface finishing, will also find useful techniques which may be applicable in the wider context of robot system development

1.1 General Background to the Project

The project was initiated when Walker Crossweller Ltd, a Cheltenham based bathroom fitting manufacturer; decided to seek possible ways of introducing more advanced technology within their manufacturing processes. Following discussions with the Manufacturing Group at the University of Bath, a major research project was proposed which eventually enjoyed financial support from both the company and the Science and Engineering Research Council.

It is concerned with the replacement of one of the manual finishing processes that occur in the production of brass bathroom fittings. The operation is known within the trade as 'scurfing' and is a manual operation that removes significant amounts of material. It occurs between the deburring and polishing operations, prior to chromium plating. The operator removes surface defects from the component by manipulating it against an abrasive belt. The task requires a high degree of skill, and is achieved through complex manipulations of the component, with continual identification of surface defects, and further selective machining. The operation is a noisy, dirty, and labour intensive, and has recently been identified as a possible cause of industrial disease.

The component geometry makes the task unsuitable for dedicated commercial automation which is insensitive to variations in the component geometry. The surface defects themselves are also randomly distributed and could only be removed by excessive machining over the entire surface which would clearly be uneconomic.

The design of a computer controlled automated system was undertaken which would incorporate the flexibility of the human polishing action, i.e. the agility to machine a variety of components with the tenacity to machine selective persistent defects. To achieve this the system requires a knowledge of its own and the component geometry in order to plan the complex movements around the geometrically complicated components, and external sensors to identify defects and control their selective removal. The features required suggest an advanced form of robotic device incorporating sensory, decision making, and path planning capabilities. Such a system is typically referred to as a third generation robotic system.

1.2 System development outline

At the commencement of this thesis the project had already been running for three years, and in order to familiarise the reader with the content of the work, a brief outline of the development of the system is included here. A more detailed examination will be found later in Chapter 3.

The project was started in 1980 and its development fell into six broad bands. These were:

i) Design of the robot configuration. This is based upon a three workhead configuration. One to hold the component and one each for machining and inspection.
ii) Creation of a modelling system for internal representation of the complex components. This will assist in path planning and also for control of the required machining and inspection processes;
iii) The development of an intelligent robotic vision system that could identify surface defects and relate their position back to a controlling process;
iv) A strategy for planning collision free paths around the component for machining and for inspection;
v) Development of an adaptive control system for programmed machining of the component surface, which can cover the entire surface or perform selective removal of persistent defects. To be achieved by sensory detection of the grinding process and the integration of machining strategies; and,
vi) Integration of all of the ideas within a single system.

After designing and building the basic structure of the robot, the initial work undertaken was the development of the modelling and inspection systems by Y.C. Choong (1). Due to a lack of CAD information on the components a triangulated model was created from data obtained from a computer controlled coordinate measuring machine. The inspection system provided a fast simple method for rapid discrimination of surface defects upon the component. This had been completed at the start of this thesis.

S. Jenkins then developed the off-line analysis of the component model to generate the path planning data for machining and inspection (2). The system breaks the component surface down into small patches which can be individually machined and inspected. This work was completed within the time span of this thesis.

The author's main task was to undertake the last two stages of the development program. As the commissioning proceeded, he was also involved in significant modifications to parts of the system developed previously which proved inadequate under test. These included a new abrasive head configuration and a path planning strategy that considers the local component geometry.

1.3 Objectives

The principle objective of this research was to develop an adaptive control system that would control the scurfing operation through the monitoring of in-process information, and the development of a series of different geometry machining heads and movement strategies. These were to be incorporated within the robot system, to enable successful machining of a variety of components. It also included the commissioning and examination of the complete robot system.

An examination of the system development at the start of the author's work identified a number of objectives:

i) Development of a sensory device to monitor the cutting intensity during the scurfing operation. This is an integral part of the adaptive control system, as a suitable measurement must be obtained to control the process for different configurations and presentations of the component to the abrasive machining head;
ii) Identification of the optimum geometry for the abrasive machining workhead. There are a number of abrasive belt configurations that could be used to scurf the component;
iii) Development of a set of machining strategies for scurfing the component whilst maintaining the integrity of its geometry. It is relatively easy to machine the component

but the action must be performed with regard to the local component geometry, otherwise the integrity of the surface geometry will be lost. Such defects become obvious after plating causing the component to be scrapped. They are not readily detectable by the inspection system and so this must be an integral part of the machining strategy;

iv) Commissioning of the system. Various elements of the entire system had been constructed and developed but they had not been tested together; and,

v) Evaluation and assessment of the system concept. After the commissioning the entire system would require testing with different components and an assessment made.

1.4 Achievements

The main achievements of the thesis lie in the development of the adaptive control system and its associated abrasive belt configuration, and the development of a series of strategies for machining the component, which consider the local surface geometry and therefore maintain the geometric integrity. Additionally a complete assessment of the system has been made using commercial components and analytical shapes. The major contributions are:

i) Development of a unique sensing device that monitors vibrations induced in the component during cutting. It has the advantage of measuring very low forces, is linear with the cutting normal force, and is not affected significantly by different components or geometries.

ii) Design and installation of a special purpose abrasive head that is capable of machining a variety of different geometries.

iii) Integration of sensors within a series of movement algorithms. These can control the machining dependent on the local component geometry and produces a satisfactory degree of surface finish.

iv) Development of a new off-line path generation strategy that creates sets of discrete paths around the component. They can be accessed with regard to the location of identified defects.

v) Commissioning of the entire robot system for a variety of different components. Analytical shapes as well as commercial components have been tested and machined by the robot.

vi) An evaluation of the system both in terms of its technical performance and future economic viability with regard to an industrial application.

vii) Recommendations for further development both in terms of this system and the application of the techniques developed to a wider variety of similar operations.

1.5 Thesis outline

In order to familiarise the reader with the current state of the art with respect to robotic finishing and the work completed by other members of the research team, chapters two and three describe the background to the project and give a review of the previous work carried out on the project. Some initial problems identified within the system that were corrected by the author are also included here.

The next two chapters describe the work undertaken by the author that were essential for commissioning of the robot system. Chapter four explains the development of the force measuring system for the adaptive control. For completeness it also describes some of the early work perfomed by another member of the research team W. Wright in investigating different sensors. Chapter five describes the basic movement software and the inclusion of the adaptive control system.

Chapter six presents the results from the first commissioning tests. Although successfully achieving most of its goals, the system did not produce an adequate surface finish. The chapter continues by describing the development of a new configuration for the abrasive cutter and a path planning strategy that will reduce machining errors.

Chapters seven and eight explain the development of the path planning strategies. The first chapter describes a method for dividing the component surface down into separate regions for individual machining or inspection.The next chapter then describes the implementation of the path planning, within each regions and between different regions. It finally describes the on-line implemenation of these ideas.

The performance of the entire robot system is then discussed in chapter nine, in particular the effectiveness of machining an analytical and a commercial component. The results from testing the two different components are presented and the system is evaluated with regard to these results. Particular areas considered are, cycle times, surface finish and the effect of component complexity.

Finally in chapter ten the conclusions, recommedations for further development of the system, and the possible application of the techniques developed to improve similar systems are discussed.

2. BACKGROUND TO THE PROJECT

Walker Crosweller's range of bathroom fittings start life as brass die castings, which have to be cleaned and machined before being chromium plated. The company wanted to examine the feasibility of replacing their existing labour intensive cleaning operations with an automated system. The complex nature of abrasive machining of a doubly curved shape, has meant that there have been few attempts to automate the process. This is due to the geometry of the components and the machining operations needed to produce a good finish.

This chapter describes the reasons for introducing automation in the company, the present automation, and the limitations of existing commercial technology. It then derives a specification for a robotic system that can replace one of the finishing operations and discusses the current research that is applicable to this task.

2.1 Reasons for Advanced Automation

The introduction of automation has been increasing throughout the foundry industry. There have been a variety of reasons for this change over the last 20 years, starting with the initial move in the 1960's, trying to improve the foundry environment, by making the place more acceptable for the employees (3). The following reasons for automation were identified at Crosweller.

i) An increase in Health and Safety regulations for men working in a hazardous environment, coupled with the identification of potential industrial diseases. These are damage to hearing, danger of handling hot and corrosive liquids, and "white knuckle", similar to arthritis, caused by the continued exposure to vibrations obtained when holding a workpiece against an abrasive belt. This has prompted the removal of men from the machining operation to an external supervisory role.

ii) A steady decline in the number of people willing to work within the foundry as they consider it is a noisy, dirty place. At the start of the project the firm still found difficulty in employing the semi-skilled labour to perform the finishing operations.

iii) The firm only inspects the components after they have been plated, allowing individual operators to assess the quality of the component in the intermediate stages. The quality is therefore subjective, and can vary between operators and batches. An automated system would improve the consistency in quality of the components.

iv) The supervision by a single operator of a number of cleaning machines would reduce the cost of cleaning per component.

v) The flexibility of an advanced machining system would prove more cost effective than a series of dedicated machines, as the system could be easily configured for a new range of components, or for modifications to an existing range.

These reasons led the University and Crosweller to examine the components and their associated machining to identify possible areas for automation.

2.2 Typical Components.

All of the bathroom and tap fittings start as either a brass or a gunmetal die casting. The general public want a product that has a bright, clean and hygienic appearance. To obtain this, castings are machined and polished to produce a high degree of surface finish before they are chromium plated. The section describes the component geometry and machining before plating.

2.2.1 Component Geometry

The typical components (fig 2.1) are highly complex shapes no longer than 180 mm. in length and weighing less than 0.5 kg. They are designed by graphic artists for aesthetic appeal and are influenced by current fashions. Additionally there are hydrodynamic

Fig 2.1 Typical Components

considerations, (to comply with strict noise regulations), but modifications are made mainly subjectively. These shapes, which have a double curvature over the majority of their surface; are then modelled to produce a mould for casting. There has been some work on designing castings with regard to the machining and cleaning operations, but the components still have features that make the objects difficult to process (4).

The components are not built up solely from primitive shapes such as planes, cones, spheres, cylinders and ellipsoids, although the majority are symmetrical about a split line and do include some of these primitives. Therefore their surface can only be represented by the intersection of high order curves or by a system such as DUCT (5). Crosweller currently design their components in a model shop and do not have a draughting or solid modeling package which can satisfactorily reproduce these curves. This means that there is little numeric data available that can mathematically describe the components. This will be rectified in 1986 when the company intends to install a CAD system to assist in the design of the castings and their moulds.

2.2.2 Machining the castings

After the casting process the components suffer from a number of faults. Unwanted material is left attached to the components in the form of risers, sprues, runners and gates which are needed in the casting process to allow the molten metal to flow. Wear or misalignment in the mould causes faults such as flash and parting lines. Oxide films, scratches, blow holes, and micro pores can also occur due to impurities in the metal and mistakes in the casting process. There will also be variations in the size of the component and its geometry due to differences in the cooling of the metal and wear in the moulds.

In order for the cast components to be plated, all of the defects from the surface of the casting must be removed. The casting is put through a highly skilled multi stage operation which comsists of the following operations:

i) Fettling where large quantities of excess material are removed. This operation is normally carried out by grinding wheels or abrasive cutters, and is used to remove flash, gates, sprues etc;

ii) An initial milling, drilling and reaming operation to produce the flat surfaces and bores needed for mounting and location. The burrs that are produced are removed by fixed grinding wheels or barrel polishing where the components are tumbled with fine abrasives in a detergent solution;

iii) A scurfing or pre-polishing operation. This is directly concerned with the elimination of surface defects and imperfections left by the casting operation, and involves the removal of large amounts of metal. The operation is carried out by hand, and the component is manipulated against a coarse abrasive belt. The belt is either supported over a compliant roller, or suspended and tensioned between two rollers. This operation not only removes defects, but must ensure that the component retains its blended geometry; and,

iv) Finally polishing using a buffing wheel prior to plating.

From analysis of the complete machining operation, the scurfing operation was identified as the most labour intensive and costly. Details of this cannot be included as they are commercially sensitive, although estimates that cleaning contributes 30 % to the casting costs have been made, largely due to severe working conditions causing a large turnover in labour (6). To understand fully the process, the worker's task must be further investigated.

2.3 The Scurfing Operation

At first glance, the scurfing operation is a relatively simple task that is performed by semi-skilled labour. The worker has to remove from the surface all of the defects left by the casting process, by holding the component against an abrasive belt. On further investigation, the operator uses a complicated sensory feedback to control the delicate grinding process. The task must be performed without altering the geometry of the component, so the selective removal of the defects must not change the smooth doubly curved surface. Therefore any region that is machined must be blended into the rest of the component, any sharp or irregular changes will become immediately apparent after plating.

The worker uses the following information to scurf the component correctly. He is aware of the component geometry and uses it to hold the component and present it against the belt. The orientation is determined by the local geometry at the point of contact. The machining direction is performed in the direction of the most significant curves. This ensures maximum contact between the component and the belt and helps to maintain the geometry. The component must be be machined in the direction of least curvature because the limited contact area would result in the forming of a series of facets.

The defects and areas for machining are identified visually by the worker. These areas are then used with the knowledge of the component to position the component for grinding. The depth of grinding is determined by the size and depth of the defects, and the state of the surrounding surface. The cutting is controlled by tactile and aural senses with the operator feeling and hearing the intensity of the cutting operation. A knowledge of the position relative to the defect is also used to aid in the blending.

The operator continues the scurfing until all of the component surface is cleaned and blended. It is important to note that the operator does not work to dimensional constraints. He is free to machine any portion of the surface to remove a defect, as long as he maintains the geometry and aesthetics of the component.

Standard NC and CNC grinding systems cannot be applied to this task because of the complex geometry of the surface. Dedicated commercial grinding machines exist, and Crosweller have had one built to their own specification, a cam operated system that scurfs one of the most popular taps in their range. The system is successfully installed, but it highlights the three main limitations that occur with this type of dedicated machine:

i) The machine is not sufficiently flexible to scurf all of the surfaces of the component and is restricted to the top surfaces;

ii) Adapting the system to a different component would involve a major redesign; and,
iii) The equipment was expensive and was only justified for a component that is popular and has long production runs.

A new approach is needed that will over come these limitations. The introduction of a robotic device will remove the three previous problems, as robots can have a large number of degrees of freedom (DoF) and can be reprogrammed for different tasks. The task has to be controlled from external inputs for the grinding and inspection stages so at least a second generation system would be needed.

2.4 Specification for Automation

Most robotic systems are currently programmed by either teaching the path to the robot (7,8), or by the use of an explicit positional part program such as VAl, RAPT, AML, etc (9,10,11). When programming a robot to move around a complex shape, teaching is used as the geometry is too complicated for explicit positional information (12). If the scurfing operation was taught to the system, an infinite number of paths would be needed to accommodate the location of every defect. A more effective method would be for the system to identify the location of the defect, and plan its own paths the features commonly found in a third generation robot device. To perform this the system would need three basic elements:

i) A knowledge of the component geometry;
ii) A methods of identifying defects; and,
iii) A control system for grinding.

To accommodate the range of components, and to achieve these three objectives, the following features are needed:

i) Five or six degrees of freedom to reach all of the component surface;
ii) A knowledge of the component geometry to aid in path planning and location of defects;

iii) An adaptive control system to monitor the grinding intensity at different orientations and positions on the component;
iv) An inspection system to identify the surface defects, incorporated with the component geometry to find their location; and,
v) A path planning strategy for moving around the object. This will direct the scurfing and inspection operations and assist in generating collision free paths for moving.

In addition, further requirements have been identified from within the casting industry to ensure the viability of installing such a system (6,13).

vi) The machine must be able to handle short runs.
vii) A simple universal chucking system is required.
viii) The system must be flexible enough to handle a variety of components.
ix) Programs must be capable of being changed quickly.
x) Machine control must be electronic.
xi) Dynamic stability.

Using these requirements a more detailed specification was drawn up. Some of the points applicable to this thesis are shown within the system specification in appendix A.

2.5 Review of Current Research

To assist in the clarity of the thesis, this section is intended as a background to the ideas behind the initial development of the project, and not as a literature review of every aspect. Individual areas of research are discussed in depth in the relevant chapters. A discussion of the inspection system which was developed by Y.C. Choong and can be found in reference 1.

The various advanced robotic techniques needed in the system are described here. To put these into context a brief description of current robot programming practices is included. Then the related surface finishing operations that exist both within installations in industry, and from on-going research projects are described. Finally, approaches to the idea of adaptive control and path planning around complex surfaces are considered.

2.5.1 Programming Robots

There are two main methods used to program servo-controlled robots:

i) On-line. Teaching the robot by moving it through a cycle; and,
ii) Off-line. Using a robot programming language.

All the commercial servo-controlled robots developed since the sixties can be programmed on-line. The method is referred to as occasionally used (7,14). There are two categories for this type of programming:

i) Continuous path. This is generally used for paint spraying and arc welding (15,16). A device, often called a teach pendant, is clamped onto the robot arm and is used to steer the robot through a cycle. The position of individual axis joint coordinates are stored either continuously by an analogue device, or digitally at small fixed-time intervals. When the teach phase is finished, the pendant can be removed and the sequence can be played back, this time moving the robot.
ii) Point-to-point. This is generally used for spot-welding, loading/un-loading tasks, and deburring (17,18). The robot is jogged into position by the operator. Depending on the robot design, it can be moved either by altering each individual axis, or by moving in a global cartesian reference frame. When the robot is in position the point can be stored. The robot moves between points by either linear interpolation or fastest movement. Functions can be included in the program that are executed when the robot reaches particular goals. These include velocity of

movement, sending/receiving signals, time delay etc. The path can be altered by changing individual coordinates.

This on-line approach is sufficient for may simple robotic tasks. but it can become tedious when there are hundreds of points that must be programmed for a point-to-point operation. A number of disadvantages have been identified with teaching a robot cycle (7,19). These include :

i) If the component on which the robot is working changes, a new cycle must be re-taught;
ii) When a new cycle is being taught the robot must be removed from the production environment;
iii) The component data for the robot application is usually defined in drawings relative to a particular reference frame, and is frequently stored on a data-base within the organisation, and this is not usually available to the programmer in a 'sensible' form.
iv) To program the taught cycle, the system relies upon a skilled operator, but in paint spraying or welding, a person who has knowledge of robot system, may have only limited knowledge of the manual operation and vice versa.
v) There is no means of predicting collision problems;
vi) Difficulty in integrating sensors with the robot; and,
vii) Not amenable to the development of computer integrated manufacturing systems.

Instead, some robot systems provide computer programming languages with commands to access sensors and specify motions. These are referred to as 'explicit' or 'robot-level' languages (7). They have a more structured programming language. This overcomes most of the problems shown above, and integrates the robot operation within the entire manufacturing system. Unfortunately this method has its own disadvantages (8,20):

i) Inaccuracies in the position of the robot. On-line programming is concerned with the repeatability of the robot. This is variance in position each time the robot returns to the same taught point, which is defined by the resolution of the control system. Off-line programming is concerned with accuracy which is the difference between the programmed move and the actual move. This will vary within the envelope of the robot and between robots;

ii) The operator needs the ability to work within different reference frames. There will be a coordinate system for the robot and a different one for the workpiece;

iii) Limited means of interfacing with the factory's data base;

iv) Limited analyse of dynamic considerations in positional accuracy and path following, due to flexibility and stiffness in the system;

v) Debugging a programmed sequence; and,

vi) The programmer must be expert in computer programming and be able to understand the sensor strategies. Hence the language is not accessible to the typical worker on the shop floor.

To overcome some of these initial limitations two different approaches have been made.

i) Utilising existing explicit programming languages such as VAL and integrating it with a CAD system (19). An off-line package creates a VAL program using coordinate information derived from the CAD data base. Typical applications are in drilling and routing of aircraft panels (21,22). The main limitations are with the inaccuracy of the robot and the difficulties in incoporating decision making capabilities based upon sensory information.

ii) A different approach is the development of 'task-level' programming, such as RAPT,AUTOPASS, and AML (23,24,10). Specific goals are defined and the motions are generated using a knowledge of the objects and the robot. They are designed mainly for assembly and handling operations and are written using simple AI techniques in a terminology that is familiar to the operator. (e.g. PLACE interlock ON bracket SUCH THAT interlock.hole IS ALIGNED WITH bracket.hole) (7,14).

The typical programming languages that have been developed are predominantly for assembly tasks. There has been little consideration of utilising off-line programming for continuous path programming in spot and seam welding, and paint spraying, due to the complex nature of the path.

2.5.2 Existing surface finishing projects

The increasing introduction of legislation for health and safety, combined with a shortage of suitable labour willing to work in the foundry environment, has increased the demand for automation equipment. Special purpose dedicated automation and industrial robots, are being installed in order to remove men from this harsh environment, and also to improve the efficiency, quality and consistency of the cast components.

Most robotic installation within the foundry are justified on the basis of introducing higher powered finishing tools which speed up process times, or replacing a loading/unloading operation where the component is too heavy or awkward for the operator to handle easily (25). In the casting finishing processes, the main areas of installation are in the polishing and fettling operations. It was estimated in 1983 that there were at least 80 installations of this type in Europe (26).

The polishing process is relatively simple because of the large amount of compliance between the polishing mop and the component. This means that there is little need for accurate path tracking around the component, and the operation can be performed with a relatively crude machine, the path easily being taught to the system. Typical areas where this has been introduced are in the finishing of car bumpers, door handles, or stainless steel sinks (17,27), which have large relatively flat surfaces. More complicated shapes have also been processed (such as elbow pipes (17)).

With fettling , the position of the risers etc. is approximately the same in every casting, and can be removed with a simple repetitive milling or grinding operation (28,29,30). Usually the robot follows a simple path which has been taught to the system by a skilled operator. Variations that are found between castings can be accommodated by spring loaded tools (26,31).

There has been no commercial progression from these systems to the scurfing operation, although a number of research institutions are looking at the machining of complex objects. The interest includes the machining of castings, shoes and shoe moulds, turbine blades and sheep shearing.

A similar project, on the cleaning of bathroom fittings started at the same time as this project, at the Institut fur Steuerungstechnik der Werkzeugmaschinen und Fertigungseinrichtungen at the Universitat Stuttgart (32). A commercial industrial robot holds the component which is moved around a fixed abrasive belt. The system is taught a start and finish point at either end of the component, and an adaptive control system maintains the grinding force by altering the position of the robot. It can be programmed to vary the force so as not to grind off edges of the component. The project stopped in 1982 with the principle being proven machining at feed rates of up to 300 mm/sec. From recent discussions the project is to be resumed soon for an industrial application. The adaptive control system has also been used for other applications notably in fettling trials.

A French project mimics a shoe manufacturing process known as of the shoe (33). An industrial robot holding a milling tool moves around the profile of the shoe. The path is taught to the system storing a binary value for the required force at each point. The milling is controlled by a separate servo loop. The robot positions the arm and a separate control system modifies the position of the milling cutter relative to the robot and the shoe.

These two systems are typical of research into the application of robots, to grinding tasks where a taught path is modified by a force control system. With one system, the position of the robot is modified, whilst in the other the robot follows a set path and a servo system varies the milling cutter's position relative to the robot . In both cases though the path is taught to the system.

A project that utilises a feedback system together with a model of the object to assist in path planning is a sheep shearing robot that has been developed in Western Australia (34). The computer controller stores a model of the sheep made up of from sets of quadralaterals. It uses these regions to plan the path around the sheep. The problem for the system is that the sheep moves due to breathing and random motion. To accommodate this, the control system detects local movement in the sheep relative to the cutter, and in real time modifies the model accordingly. The feedback relies on a proximity sensor to determine the distance from sheep's skin to the cutter. The system can successfully shear selected portions of the sheep, (back and stomach), and strategies are being developed to accommodate other parts.

Two important points that will be needed with the scurfing system, are a means of path planning around the various complex shapes, and methods of adaptive control of the scurfing process. Both must be examined further.

2.5.3 Path Planning

Off-line path planning and it associated problems must be considered for the scurfing operation. It is a neglected area of robotic research when considering complex geometry shapes, as most research is based upon the development of high level languages in order to control assembly and manipulatory operations (22).

The first instances of robots interacting with complex shapes started with the early robots that were used for painting and welding. Here it was deemed faster to teach the task to the robots rather than have a control system that could be programmed.

A related area where off-line path generation has been actively pursued, is the generation of CNC data for machining of complex geometry shapes. There has been research and commercial installations, mainly within the aircraft industry, where paths need to be created in order to machine the aircraft skin. The aircraft surface is usually generated by a CAD system, and then various software packages are used to interface to a CNC machine tool (35,36). This is particular evident in machining of sculptured surfaces where complex machining paths can be generated off-line to provide the NC tool path data (37).

Generating robot paths around complex shapes has usually only been considered for specific applications. This can occur where the paths themselves are too complicated for the operator to teach.

Instead they are generated off-line on a more sophisticated system (38), and then sent back to the local robot controller. Off-line toolpath calculation has also been used where there is repetitive operation, and when a more accurate orientation or position of the robot is needed, than that that can be generated by the programmer using a teach pendant. There are robotic installation where robots are used to replace repetitive drilling and routing operations (20,38). This has created large savings in the teaching time.

Other areas where robots have been installed are in the laying up of composite fibres and their subsequent machining and finishing operations e.g. profile routing. All of these robotic operations which use off-line path generation demonstrate one of the main problems, the accuracy of the robot. To overcome this the robot is positioned closely to the component, and a template or drilling jig is used for the final positioning. The workhead on the robot must be compliant to allow for the re-aligning.

In all of these versions and in the sheep shearing discussed earlier, in order for the system to generate the paths it must have a knowledge of its own and the component geometry. The main database source for the coordinate information is usually the CAD system but dedicated modelling systems are also used. Due to errors in the computer model, and with the accuracy of the robot, the generated paths are not accurate. These can either be updated by information derived from the robot's position and sensors, or just used as a basis for the move with an adaptive control system altering the path.

2.5.4 Adaptive Control

To control the automated scurfing operation correctly, the system needs to monitor the grinding to ensure a constant cutting intensity and thus obtain a regular surface finish. Adaptive control is a means where through monitoring of in-process information, a measurement of the current process conditions can be obtained, and the factors governing the operation can be altered to bring the conditions within a desired tolerance. It is a technique that has been successfully introduced to CNC machining (39), and robot seam welding (40). In grinding by deciding if the interaction is either too severe or too light the relative position of the abrasive head to the component can be altered. A number of different methods have been employed on automated finishing systems.

On simple fettling systems, discrepancies between the component and the programmed path are compensated by suspending the cutter on elastic, rubber or pneumatic elements. The technique has proved very successful for light deburring operations (26,32).

The initial development for adaptive control of the grinding process has been in the control of CNC grinding machines with the objective of removing the operator from monitoring the process. The operator controls a number of parameters to optimise the process, e.g. the wheel speed, work speed, and feed rates. This is performed by relying on the operator's knowledge and skill. Through the introduction of adaptive control the time of machining can be reduced, and desired surface finish and size can be obtained efficiently with reduced tool wear (39,41).

The most common method for monitoring the grinding is by use of force transducers mounted in the abrasive head. These can either be strain gauges or dynanometers (33,39). For robotic applications the system then needs to translate the forces into the coordinate system of the work head to obtain the tangential, normal and torsional forces involved. When these are further analysed the head can then be moved.

It is possible to monitor the grinding forces through the effects on the system, the power input to the grinding motor, or variations in belt tension or motor speed (42). Other methods that have been tried are the measuring of the size of burrs in a automated deburring system (17), and the monitoring of the acoustic emission from the system. This is a known phenomenon occuring in materials undergoing stress, and can be used to determine the effectiveness of the machining and the tool wear (43).

2.6 Concluding Remarks.

Of the finishing operations that are used by Crosweller in making their chromium plated fittings, the scurfing operation was identified as the most labour intensive and costly. Although some automation has been performed in this area, it is usually fixed cycle and insensitive to variations in the components. It was therefore decided to replace this operation with a robotic system that could perform the task.

Most robotic surface finishing is performed by relatively unsophisticated systems, that either employ first or second generation techniques. They are used predominantly for painting, fettling or deburring, and are unsuitable for the complicated geometry of the scurfing operation.

To successfully accomplish this complicated surface finishing operation the following features must be incorporated within the robot system. A machine vision system to inspect the surface finish, an advanced path planning strategy to allow interaction between the robot, the complicted geometry, and the location of surface defects, and an adaptive control system to control the abrasive machining process. To accomplish all of these tasks the system must have a knowledge of its own and the component geometries and be interfaced to a number of external sensory devices for inspection and monitoring. Research within these areas is thin and is usually only applied to the simpler fettling and deburring tasks, although a number of techniques for monitoring the abrasive process could be employed.

3.RESUME OF PREVIOUS WORK

This chapter describes the work carried out on the project by other members of the research team, in particular the PhD work of Y.C. Choong and S. Jenkins (1,2) concerning the inspection and path planning strategy. It also covers the early modifications made to the hardware and the software by the author. The breakdown of this work falls into three main sections:

i) The robot including the drive systems and inspection system;
ii) The computer configuration describing the hardware and communications protocol; and,
iii) The control strategy with its associated software for off line path planning and on line control of the robot.

3.1 Description of the robot

There were various limitations with the commercial industrial robots that were available at the start of the project:

i) Cost;
ii) Poor repeatability and accuracy;
iii) Little or no capability for interfacing to external sensor based control systems and geometric data bases; and,
iv) Unsuitable kinematic design.

With these considerations in mind it was decided to construct the robot in house using a modular approach.

3.1.1 Robot configuration

The combination of many degrees of freedom (DOF) that do not operate independently, as in an articulated arm, means that positional errors are cumulative. If each degree of freedom is independent of the rest of the configuration then the combined

Fig 3.1 The Robot

errors will be less. In addition linear motions are preferable, as revolute joints are a high source of errors, a small angular displacement being amplified by the length of the arm.

On the robot a modular approach is used for each axis. To simplify the incorporation of a inspection and a polishing system the robot is divided into three sections (fig 3.1 & 3.2):

i) The work head - for chucking the component;
ii) The polishing head - holding the abrasive cutter; and,
iii) The inspection head - holding the inspection system.

The work head has three DOF and the. polishing and inspection heads have two DOF apiece. The sixth DOF is introduced by allowing the cylindrical polishing roller to take up any orientation around its curve and similarly with the inspection system allowing the image to assume any orientation.

The three arms have a main box section constructed from aluminium for lightness. Each arm has a linear motion and a rotary system driven through the middle of the arm (fig 3.3 & 3.4). In addition the work head has a pitch motion (fig 3.5). This pitch motion interacts slightly with the linear motion and has to be compensated for. This relatively light axis is the only one which operates against gravity. The seven axes used in the robot are defined as follows.

1 Work head pitch.
2 Work head linear motion
3 Polishing arm linear motion
4 Camera linear motion
5 Work head revolution
6 Polishing head revolution
7 Camera revolution.

The polishing and inspection heads are mounted orthogonally to the work head upon a fabricated steel frame (fig 3.1). The independence of each head means that modifications are relatively simple

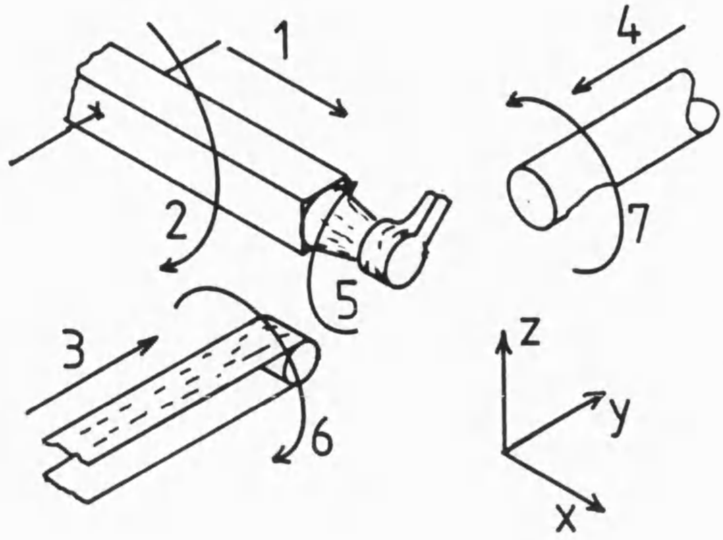


Figure 3.2 Axes of the Polishing Robot

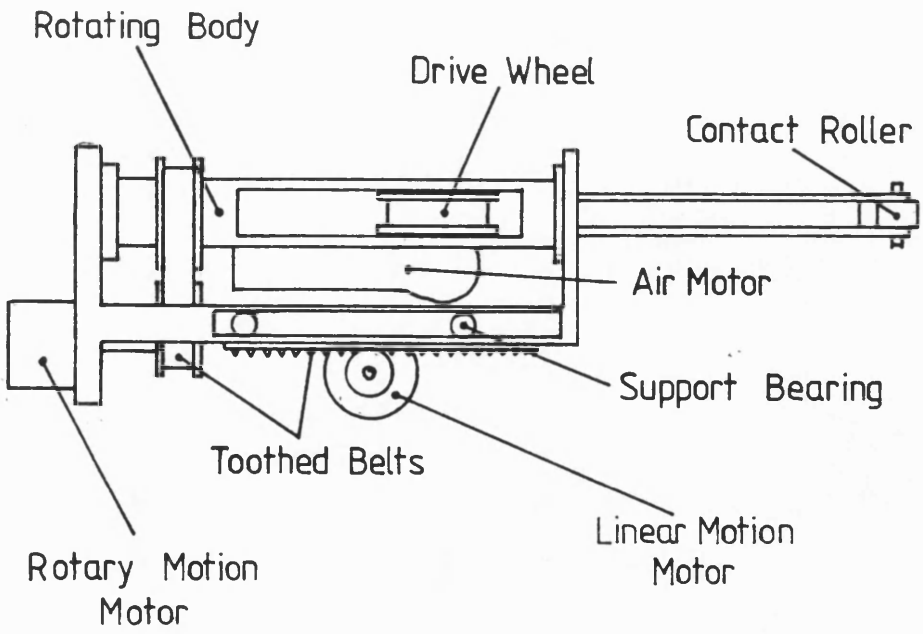


Figure 3.3 Abrasive Head

3.1.2 Drive system

All axes on the robot are driven by stepper motors. These are Sigma series 20 motors driven by the 53/1 drive cards which are configured to give 400 steps per revolution. The drive cards have two inputs, a step bit that activates each step, and a direction bit that controls the direction of rotation of the motor. Both inputs operate digitally between 0-12 V. D.C. and are buffered by a Darlington array. With this type of stepper drive card, the controlling processor must send out the steps for each movement of the robot.

The drive for each axis is passed initially through a gear box. These vary between 10:1 and 25:1 reductions for the different axes. The linear motions and the pitch motion are driven by a toothed belt, with the linear motion using nylon rollers as bearings. The rotary motion for the polishing and inspection heads are also driven by a toothed belt. This has the effect of rotating the entire polishing arm but only the light viewing apparatus for the inspection. A shaft running the length of the workhead arm rotates the chuck that holds the component.

When commissioned the robot developed two problems with its drive system. The first concerned the backlash generated by the gearboxes. After a short time of operation the backlash was found to be increasing in the gearboxes rising from about 10 steps to 50 to 60 steps. On axis three this translated to 3 to 4 mm. of movement. Secondly the bearing surface of the nylon rollers that are used for supporting the linear motion are also used to constrain the arms. This resulted in a high level of stiction on axis 2.

3.1.3 Polishing head

The scurfing operation is to be performed by an abrasive belt. The polishing head consists of the prime mover for the abrasive belt, a guide system and a contact roller mounted at one end (fig 3.3). The prime mover is interchangeable and can be either a small compact air motor or an electric motor. The abrasive belt is guided by a series of jockey wheels constructed from an abrasive resistant plastic. It then passes over a small 20 mm. diameter contact roller

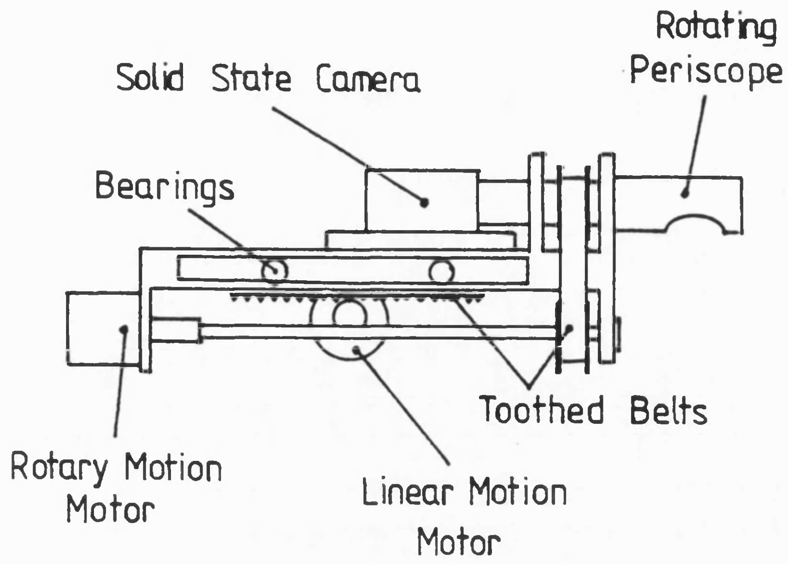


Figure 3.4 Inspection Head

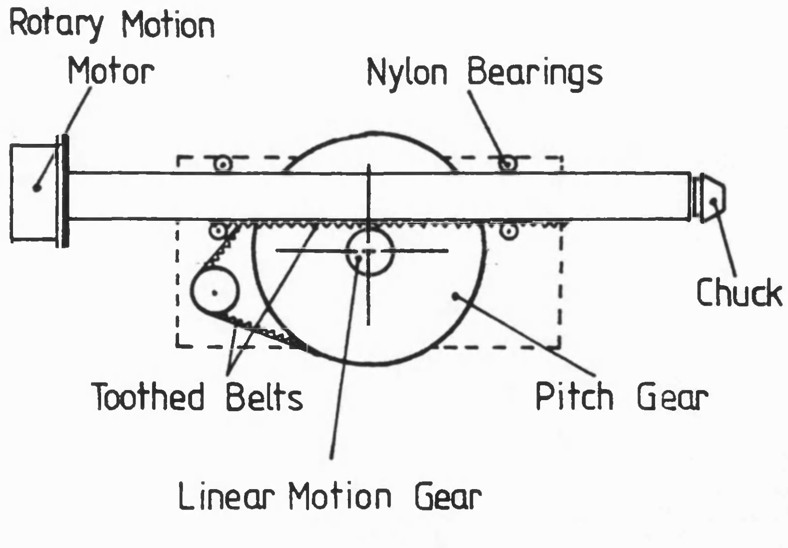


Figure 3.5 Robot Workhead

with a thin rubber coating to give compliance. The small roller was chosen to give access to concave portions of the workpiece.

Most commercial belts are constructed by butting together the two ends of a single strip and adding a short backing strip over the join (fig 3.6). This join was found to cause dynamic instability and the belts were replaced with an in house design. These are made from standard abrasive tape usually 120 grit bonded onto a 3M backing strip. By splicing the join at an angle and backing the entire length of the belt the excitations were reduced.

3.1.4 Viewing system

The viewing strategy and hardware were developed by Y.C. Choong and a detailed description of both can be found in reference 2. This section gives a simple overview of the system.

The vision system has been designed to avoid the complications, such as blooming shadows or specular reflection that may arise when oblique or uncontrolled lighting falls onto a complex shaped component. The periscope arrangement (fig 3.7) gives effective scanning with minimum movement of the camera. Lighting is coaxial with the viewing direction and is supplied by a ring of optical fibres connected to a remote quartz halogen light source. The intensity of the light source is under computer control. The periscope section also has a compressed air supply that prevents the deposition of dirt onto the mirror and cleans the workpiece area under inspection.

The camera is a 64 x 64 pixel solid state device which is interfaced to a 4 bit fully parallel A/D converter giving digitised images of 16 grey levels. Two images can be stored in the system's dedicated memory. The base level of the A/D converter is also under computer control to suit particular illumination conditions. The camera adopts a fixed focal length of 35 mm when inspecting. This gives a field of view of 20 x 20 mm. with a resolution of 0.1 mm per pixel. This relatively coarse resolution is a compromise between the ability to detect small defects and the amount of information that must be processed if real time inspection is to be achieved.

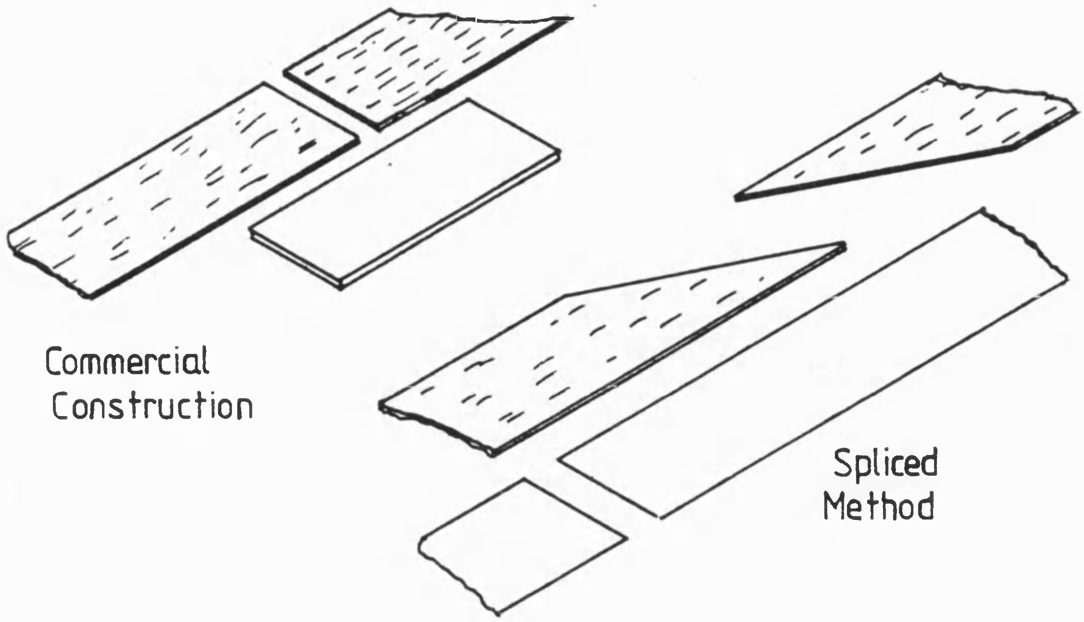


Figure 3.6 Joining the Abrasive Belt

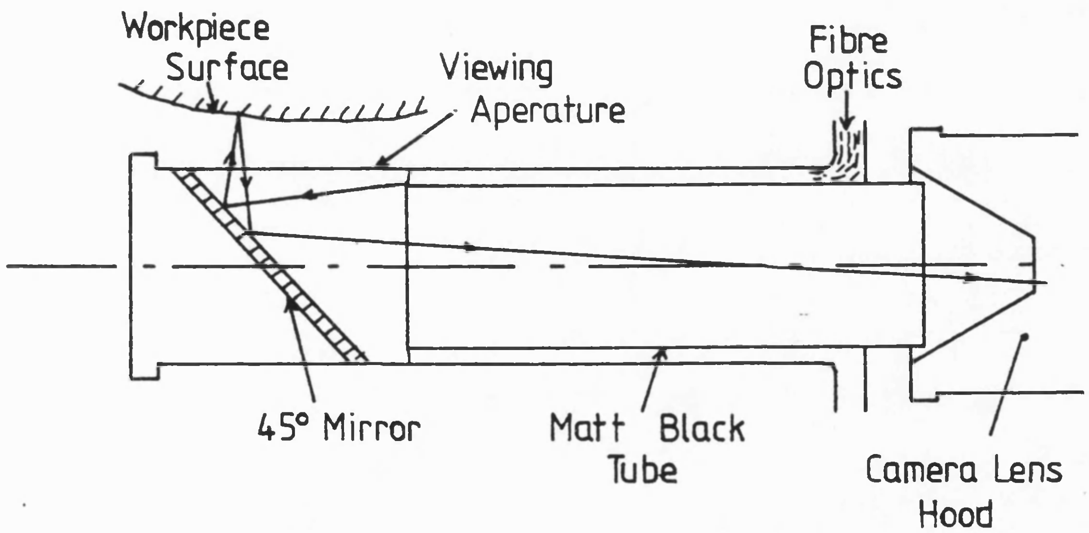


Figure 3.7 Inspection Head Periscope Arrangement

3.1.5 Robot coordinate system

The coordinate system that defines the computer model of the component is also used for the coordinate system of the robot. The main reason for this is that all path planning can be done in the coordinate system of the component and not in that of the world, so when the component is moved all of the data need not be transformed. The control system sees the component held at a fixed point in space with the robot rotating and moving about it.

The origin of the robot is taken at the endface of the workpiece arm which caters for variations in the chuck dimensions. A right-handed set of axes are formed by taking the X axis as normal to the endface, the Y axis as parallel to the polishing and inspection arms, and the Z axis as normal to the XY plane (fig 3.8).

The positions of the inspection and polishing arms are defined by two vectors and a point. In the case of the polishing arm these are the centre of the roller (x,y,z), a vector specifying rotation of the arm that lies along the rollers axis (a,b,c) and a vector running running parallel to the linear motion (p,q,r). The inspection is defined as the centre of the mirror (x,y,z), the line of sight of viewing (a,b,c) and the linear motion (p,q,r) (44).

In this thesis the following coordinate systems are referred to:

a) The motor coordinates. Taken as an absolute counter from the zero datum in terms of the number of steps for each motor. There are seven elements to this system, one for each motor;
b) The robot coordinates. As defined above; and,
c) The component coordinate system. A right handed cartesian system using the datum of the chuck location face in the direction of the axis of revolution.

3.2 Computer Layout

The control system is based upon a DEC LSI 11/23 system running RT11 V4.0. The main processor has two slave processors to which programs can be down line loaded via a serial line using MRRT 11. The processors are

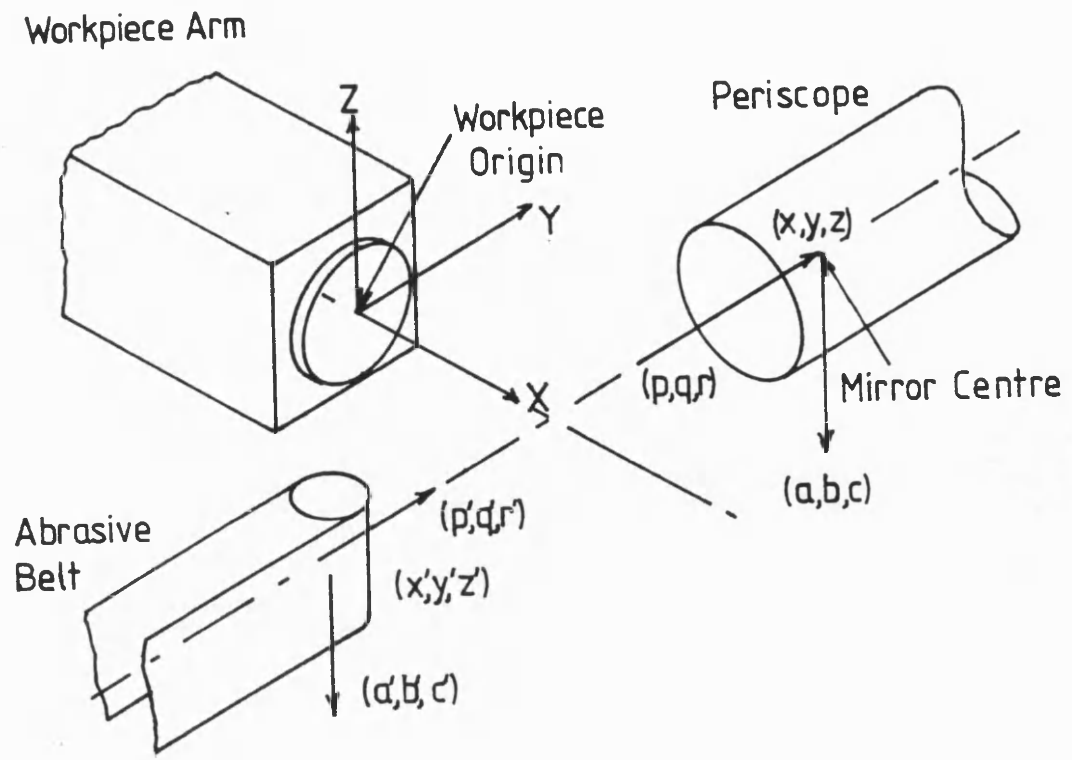


Figure 3.8 Robot Coordinate System

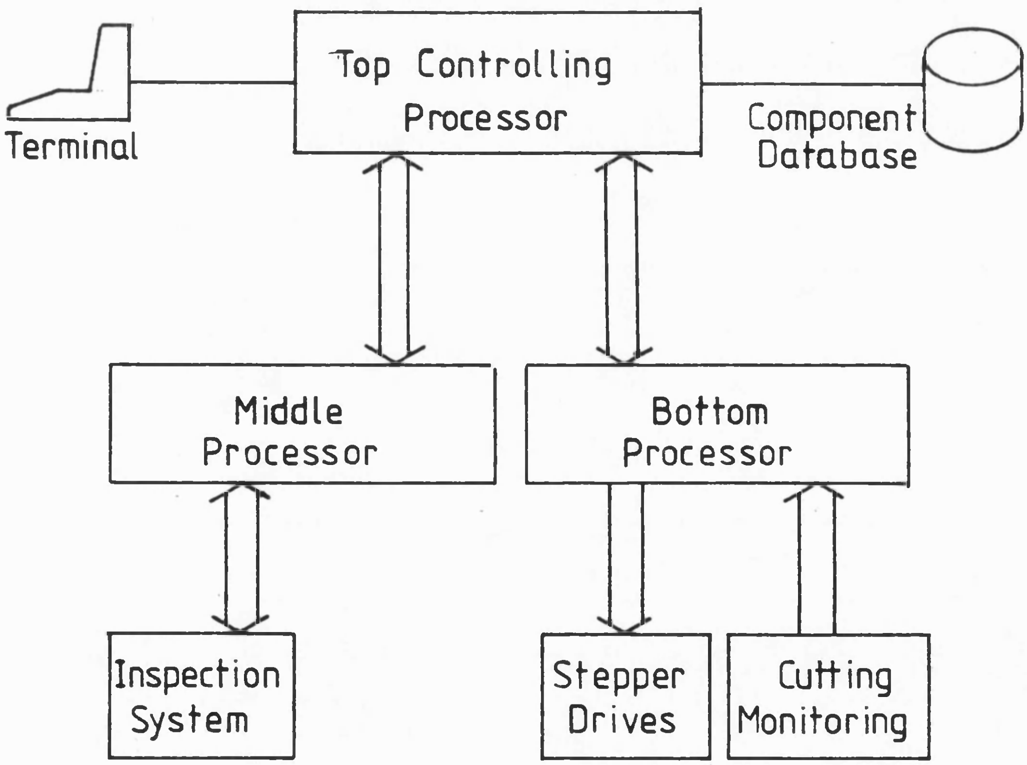


Figure 3.9 Three Processors Configuration

usually referred to as TOP, MIDDLE and BOTTOM configured so that the middle and bottom processors are the slaves of the top master processor (fig 3.9).

The three systems contain the same basic elements. An LSI 11/23 processor with a KEF 11-A floating point unit to speed up calculations for the top and middle processors, 64K of memory for the top, 56K for the middle and 24K on the bottom, serial lines for console and downline loading and a parallel interface which has four 16 bit lines for communications between processors and for interfacing to external devices. The top system also has two 1M floppy disc drives and a 12M removable hard disc.

The three processors are assigned different tasks for the control of the robot system. The bottom processor is dedicated to the movement of the robot. It is interfaced to the stepper motor drive cards and used in monitoring the feedback for the adaptive control system. The middle processor controls the inspection. The top processor is in overall control sending information to the bottom processor for movement and receiving the results of the image analysis from the middle. It is also concerned with path planning for the robot. The two slave processors use two of the parallel ports to communicated with the top. One of the ports is set to read data whilst the other is for writing.

The department also has a VAX 11/730 running VMS on which programs can be developed and tested before they are transferred to the local system.

3.3 Control strategy

The combination of the robot interacting with the complex component and the replanning of paths around its surface would lead to a high computing load. To reduce this overhead a series of planned paths are generated and stored. The paths are devised by dividing the components surface into patches, and determining a safe surface which encloses the object (fig 3.10). The inspection and polishing heads can be moved around the safe surface without having to consider collisions in real time. Paths are also generated between the safe surface and the patches.

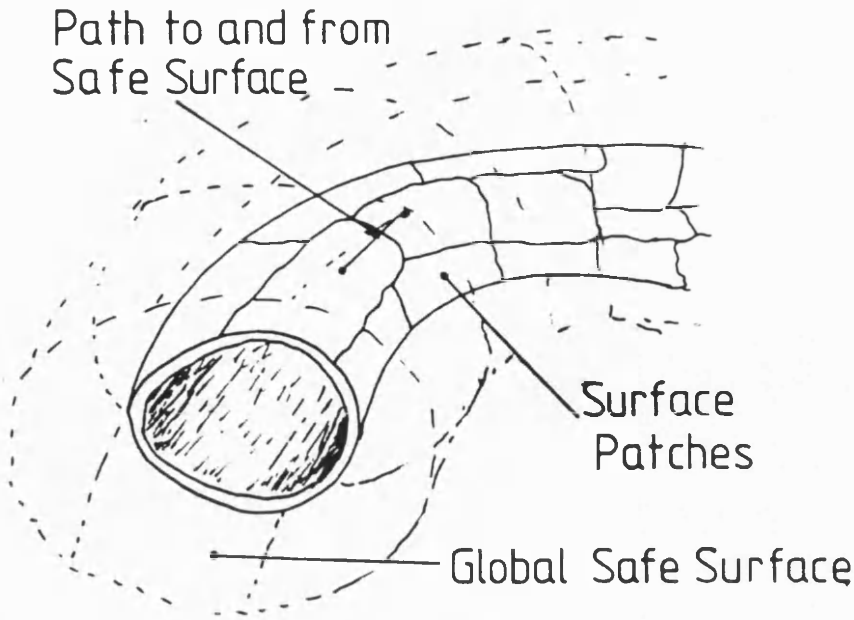


Figure 3.10 Component Safe Surface

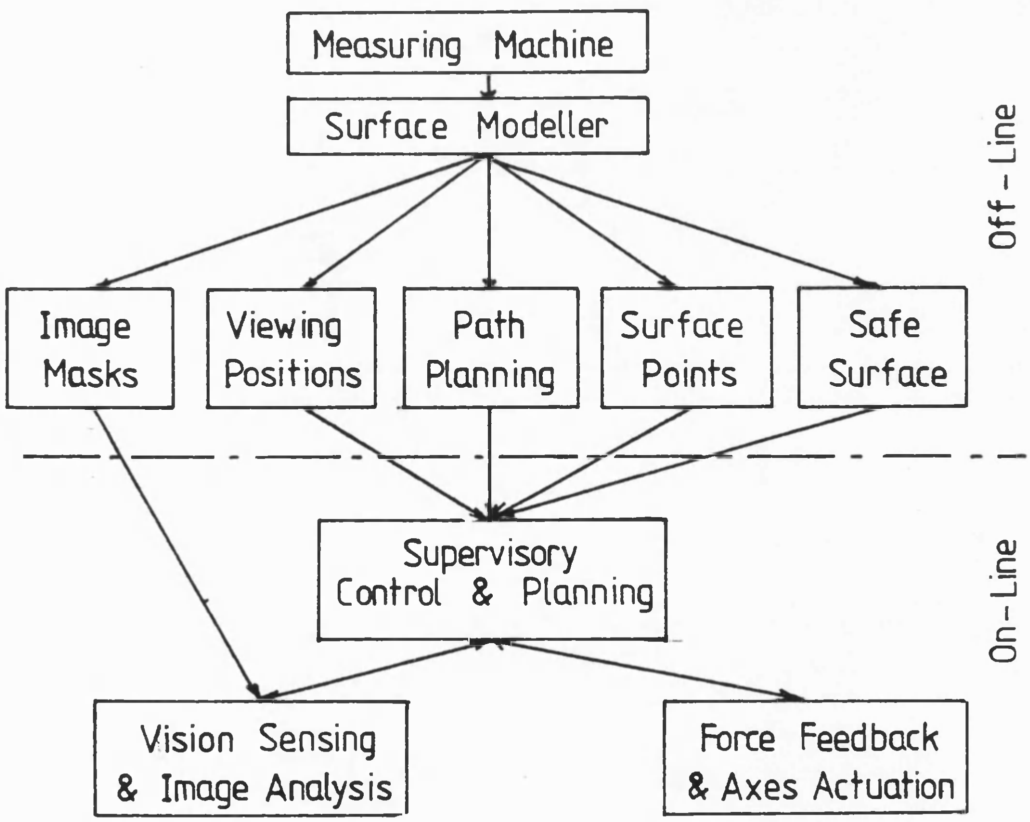


Figure 3.11 On-line and Off-line Tasks

A motion can be considered as a combination of pre-planned paths to and from the safe surface, and real time calculations of paths between patches and around the mathematically simple safe surface. In this way a balance can be obtained between an entirely predetermined NC path strategy, the problems attempting complex shape interrogations in real time, and the storage of an unacceptable number of precomputed paths.

The same surface patch system is to be used to break the surface down into areas for inspection purposes . This enables the viewing strategy to take into account the geometry of the component, to prevent image analysis errors due to the system analysing portions of the component that are angled obliquely to the camera. The edges of the component must be also known for each viewing position so that the background can be ignored.

The strategy and software fall into two categories:

i) The off-line analysis of the component; and,
ii) The on-line control of the robot.

The off-line tasks include the generation of the computer model and of all paths and viewing data. The on-line task uses the path data and feedback from the robot sensors. to control the scurfing operation (fig 3.11).

3.4 Off-line

All polishing, inspection and movement data is generated with regard to the component geometry. A model, based upon the fitting of a series of inter-connected triangular elements to the surface, is used to represent the component. The triangles give discrete information at the vertices for position and the direction of the surface, which can be interpolated to cover the rest of the surface. The section explains how the model is generated and shows how the surface is broken down into regions for inspection and polishing.

3.4.1 Triangulated Model

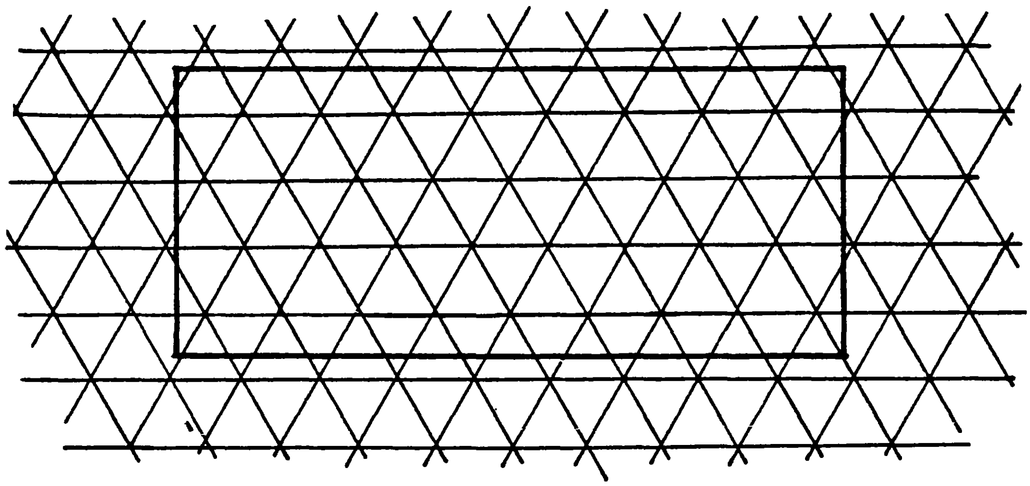
The various components are not defined using a CAD system, so the computer model is generated from physical measurements. As the majority are symmetrical about a split line, only one half of the component needs to be measured in order to produce the model. A computer controlled coordinate measuring machine equipped with a touch trigger probe is used to create a discrete array of height ordinate data and a linked series of points spaced approximately 4.5 mm. apart defining the component outline (45). Onto this 2-D outline is laid a mesh of 4.5 mm. equilateral triangles (fig 3.12). Only whole triangles that are completely inside the outline are considered. The points on the outline are then linked to the internal triangles creating a complete triangulated mesh which covers the entire component.

The mesh is now considered in three dimensions by taking the height ordinates that were generated by the measuring machine. A heuristic approach is now used to try and make all of the links in the mesh the same length (fig 3.13). The process is referred to as triangulation and was developed by Y.C. Choong (1).

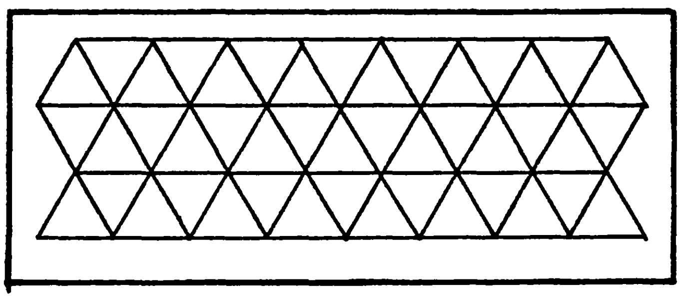
The triangles are considered as a series of nodes with defined linkages. The process perturbs the nodes until a specified number of links fall within an acceptable tolerance of the ideal link length. The process finds the least acceptable link and modifies it as follows.

The surrounding inter-connected nodes are gathered and perturbed in sequence, rippling outwards. The polygon formed by the surrounding nodes is searched until a new position (x',y',z') is found which minimises the function F(x',y',z') (fig 3.14). The function F is defined as the sum of the square of the deviation of the connected links from the ideal link length. The point being found by an iterative search process. If the link length is still outside the specification further action is taken depending on its length.

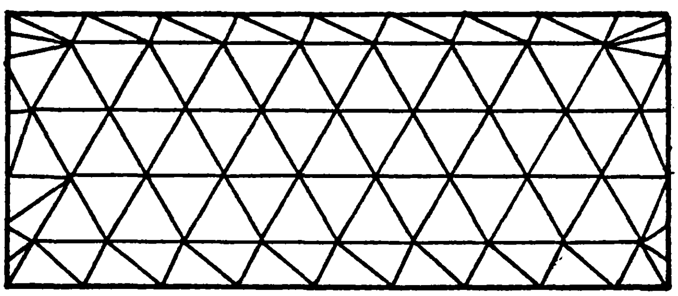
The operations performed on out of sized links are shown in figure 3.15 Short links are removed by collapsing the nodes together and the resulting new structure is perturbed outwards, rippling through the connected nodes. Long links are replaced by a new node



Stage One



Stage Two



Completed Lattice

Figure 3.12 Generation of Lattice

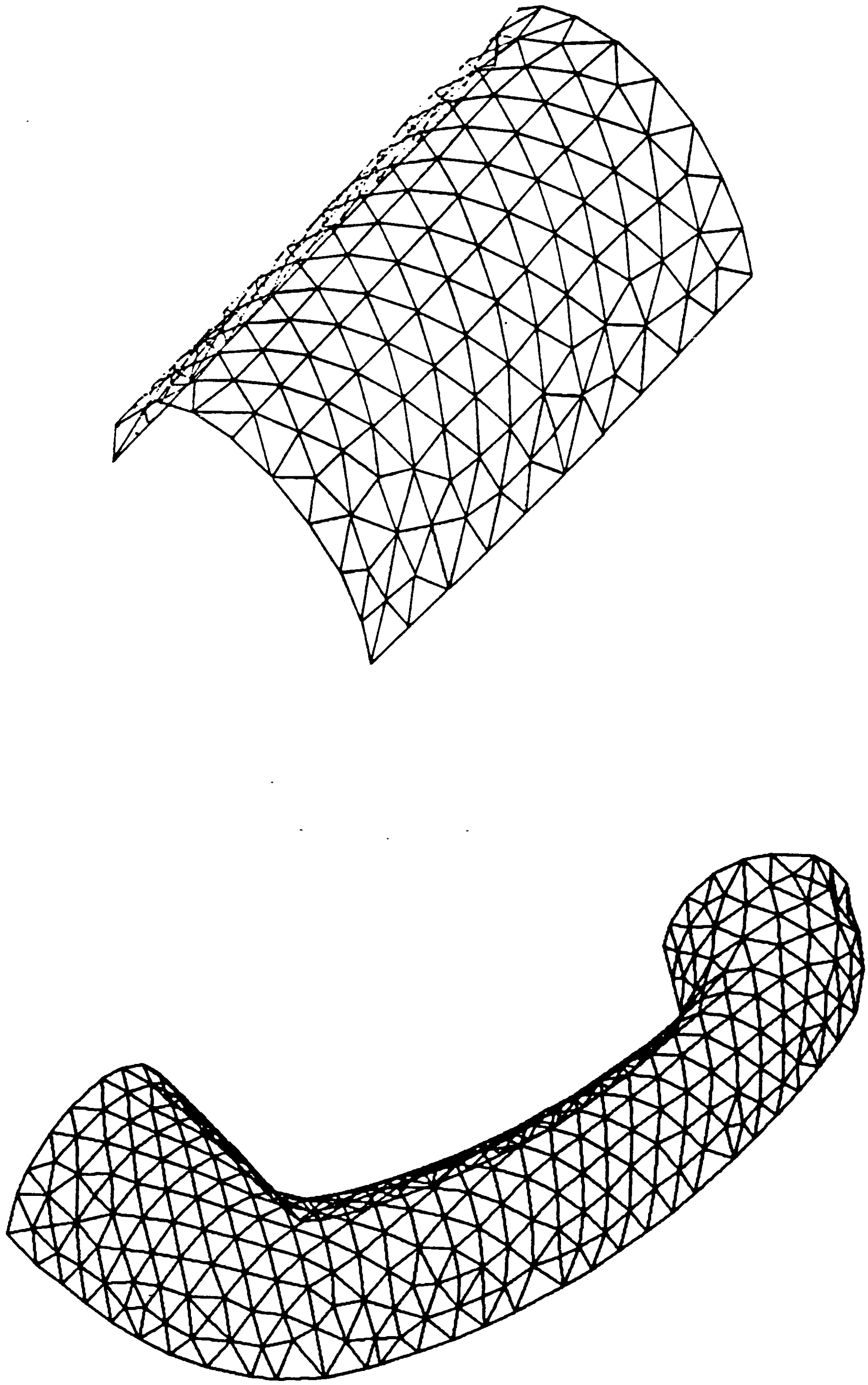


Figure 3.13   Triangualtion of component

midway along the link creating four new links. The structure is rippled again. To prevent the same nodes being repeatedly improved, a 'dead' list is used to force the heuristic process to address the entire structure.

The process repeats until an acceptable solution is obtained. The model can now be mirrored about the split line to produce a complete representation of the surface.

3.4.2 Group generation

To produce the pre-planned paths and to generate the viewing masks it was proposed that the surface be divided into patches. These patches are made up of an inter-connected set of the surface triangles which are referred to as groups. The same groups are to be used for polishing and for inspection. They are created by adding together the triangles from the surface model using the following criteria.

i) A triangle must be edge connected to the group
ii) A triangle must not be in another group
iii) The triangle vertices must be within a specified distance of the group centre. This ensures that the triangle will be within the field of view of the camera. The distance was set to 10 mm.
iv) The direction cosines of the triangle's normal must not deviate by more than a specified angle from the group's normal. This ensures that parts of the surface that are angled obliquely away from the viewing direction are excluded. The angle was determined experimentally to be of the order of 10 degrees (1).

On adding a triangle, the group centre and direction cosine (DC) are updated. The process is repeated until all the triangles on the group boundary have failed one of the conditions. A nearby ungrouped triangle is now used to start a new group. When there are no ungrouped triangles the process stops. An attempt is then made to make all neighbouring triangles similar in size by moving triangles from large to smaller groups. The size and shape of the groups

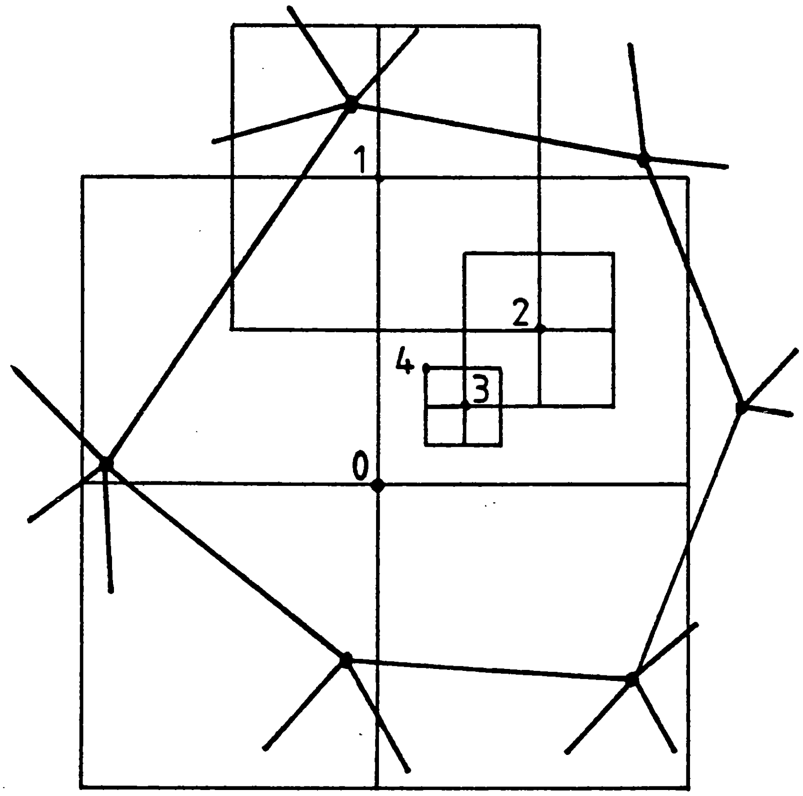


Figure 3.14 Optimisation of Vertex Position

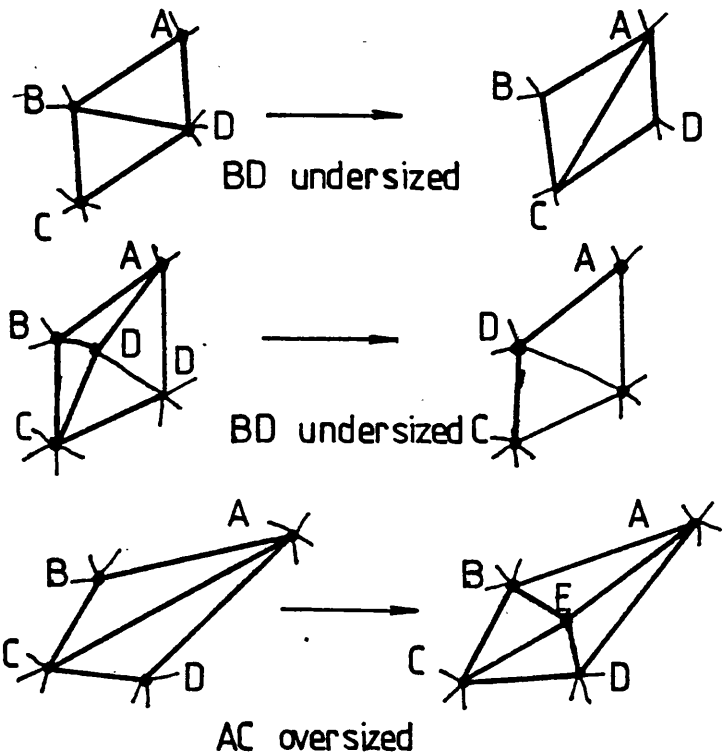


Figure 3.15 Modification of Out of Spec Links

produced reflects the geometry of the component. A complex shape gives lots of thin groups due to the curvature constraint (fig. 3.16), whilst a less complex component gives rise to larger groups restricted by the field of view of the camera.

For inspection purposes, the viewing mask is derived from the group boundary. The mask is encoded to simplify the storage and is based upon the scan lines in the image (fig 3.17). Each scan line is tested to see if it passes through the group. Where it intersects with the boundary the image coordinates are stored. A pair of coordinates signifying changes from inside to outside of the group are stored as two bytes in an integer word. As more than one intersection can occur on the same scan line the msb of the last word is set to signify the end of a line. The first word in the list of mask data is used to store the start line and the end line of the mask.

3.4.3 Surface polishing points

In order to evenly polish the surface the abrasive head must pass over the entire surface of the polishing group. Paths are required between groups and to and from the safe surface. When the component is scurfed by hand the operator does not follow the same path every time. In removing a defect repeated machining in the same direction from the same point would not maintain the surface blended geometry.

To avoid the storage of a large number of discrete paths, a strategy was derived that uses a set of points distributed evenly across the group, with the polishing head randomly visiting every point. The even distribution is accomplished by utilising the regular structure of the triangulation using three different types of point (fig 3.18):

i) Exit points. These are connections to the mathematical safe surface. It is taken as the centre of the polishing group;
ii) Bridging points. These are points that have a corresponding point in a neighbouring group. They are taken as the midpoint of the common boundary between groups; and,
iii) Polishing points. These are evenly spread across the

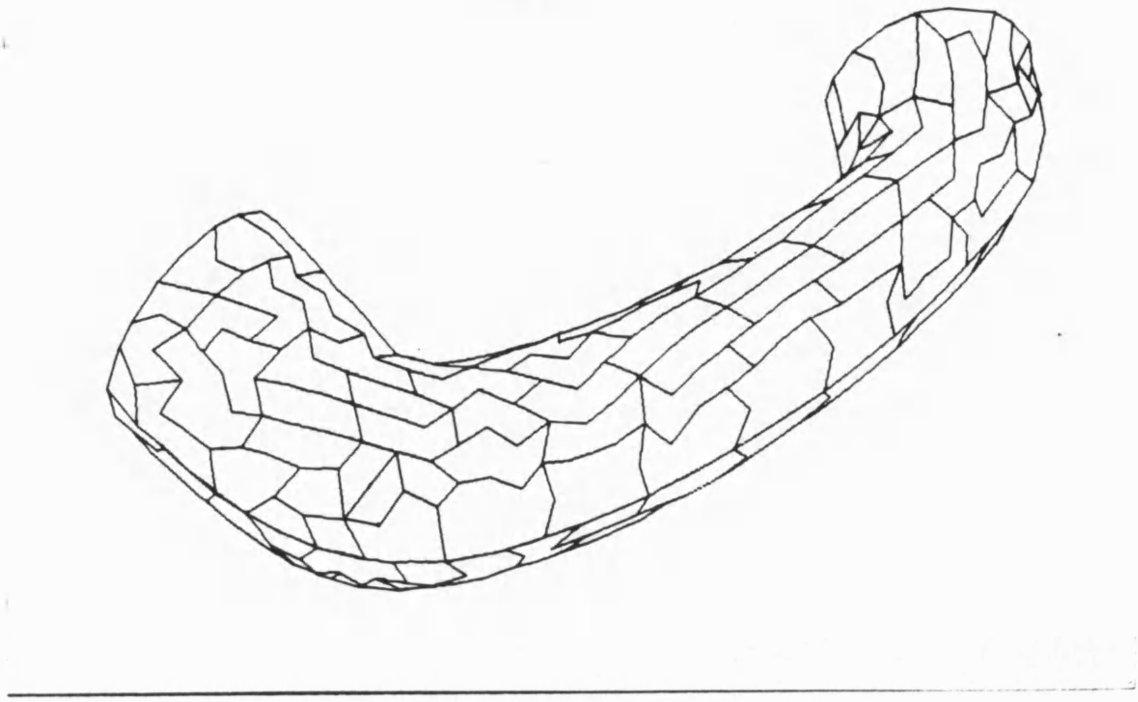


Figure 3.16 Grouped Component

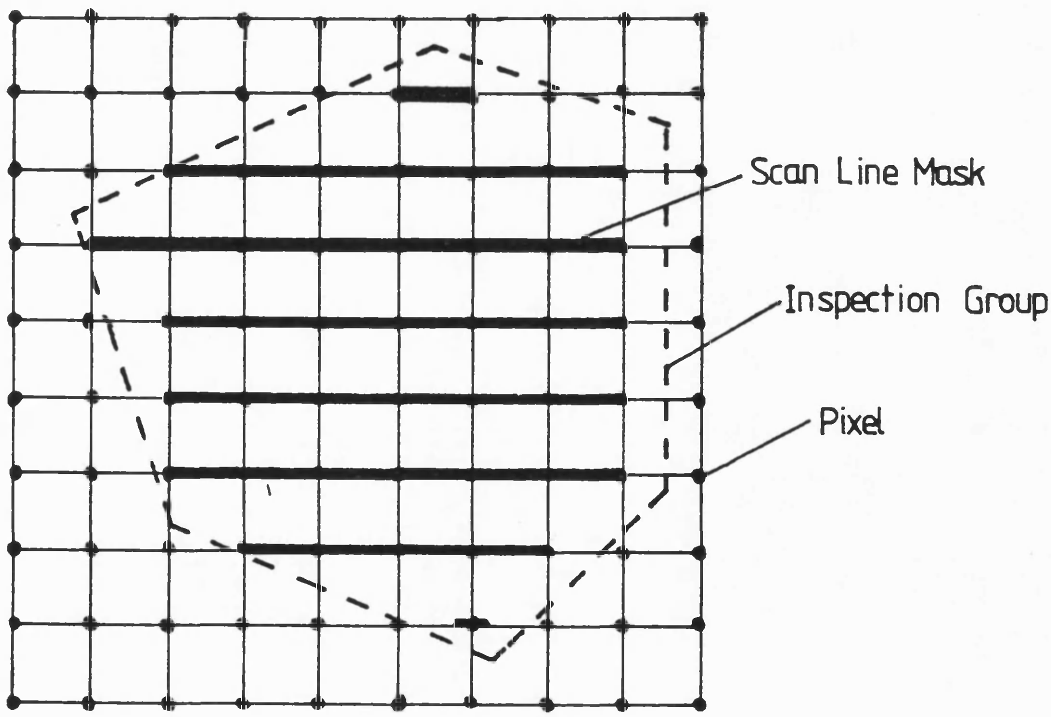


Figure 3.17 Scan-Line Mask

surface and are assigned to vertices and centres of triangles provided they are not too close to a previous point.

When a point is selected the position and orientation of the polishing head is calculated. The direction of the head is defined by the vector pqr (fig 3.8), and is selected as being along the surface normal of the point. The head has no X component as the arm is constrained orthogonally to the work head. Hence the Y and Z component of the surface normal define pqr. The centre of the polishing roller is calculated from the surface normal, the coordinates of the surface point, and the roller radius. To ensure even polishing the contact between the roller and the surface must be optimised and this defines the vector abc. The rotation is calculated by intersecting the surface with a plane that passes through the centre of the roller and contains the surface normal (fig 3.19). A tangent is taken to the surface in the plane and perpendicular to pqr. By rotating the tangent about the axis defined by pqr, the best conformity is found by measuring the area between the tangent and the model along the line of intersection of the plane.

To simplify the route planning around a group each of the surface points is linked to a number of its neighbours (fig 3.18). The links are made using the following criteria.

i) A link must not intercept another link or pass through another polishing point.
ii) The angle between links from the same point must be greater then 20 degrees.
iii) A link must not pass within 1 mm. of another polishing point.
iv) A link must not pass outside of the polishing group

3.4.4 Robot coordinate transform.

Each position of the robot is uniquely defined in the robot coordinate system by a point and two vectors abc and pqr (fig 3.8). The point xyz on the cutter arm is at the centre of the roller

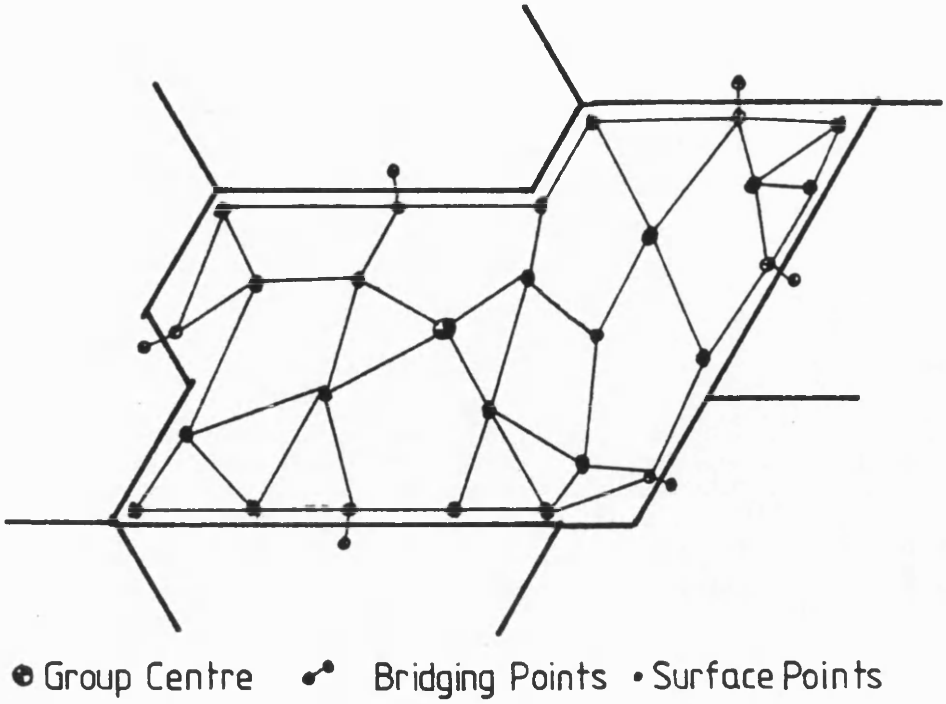


Figure 3.18   Surface Points and Links within a Group

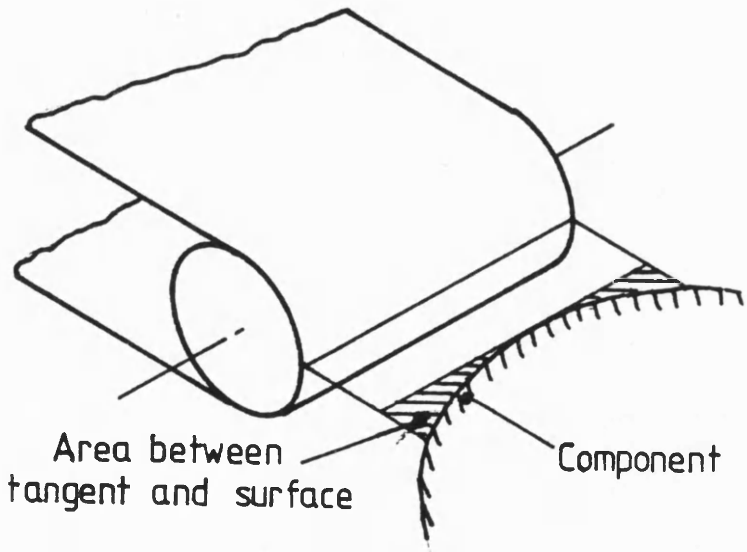


Figure 3.19   Selection of Roller Orientation

axis with the vectors abc and pqr defining the orientation.

On the camera arm the fixed point is at the centre of the mirror and the direction cosine abc defines the line of sight, and pqr determines the orientation. The position xyz is defined by the coordinates of the centre of the viewing group, the vector abc and the focal distance of the camera.

The positions are transformed into the motor coordinates which are defined as an integer number of steps away from the origin of each axis. The positive directions of the axes are shown in figure 3.8. To move to a position the angle of rotation for axes 1,5,6, and 7 and the lateral movement of axes 2,3,4 have to be calculated. The position is calculated relative to the zero position so the robot must be moved to this position and zeroed before any move can take place. Thereafter all moves are made relative to this point. The transforms and equations for the conversions are described in appendix B.

3.5 On-line

To reduce the overhead in calculations of the on-line positions, the coordinate data are considered in the motor coordinate system, i.e. in terms of steps of movement for each axis. All information is stored in integer form and there is no need to transform the data. The on-line strategy can be broadly divided into two areas:

i) The means of inspecting and polishing the groups; and,
ii) The path planning between the groups.

3.5.1 Inspection

To ensure that the image analysis is performed in real time a quick and simple inspection strategy has been devised (1). Defects have a lower reflectivity than their surroundings and can be identified by using a simple single level intensity threshold. This technique provides rapid discrimination between the surface and the defect but its sensitivity will not suit all surface and lighting conditions. The main variation in the lighting is due to the polishing operation. As the brass is buffed it reflects greater amounts of light and the image is soon outside the dynamic range of the camera.

A second stage of analysis is used to avoid this problem. The image is digitised after reducing the illumination and by hardware stretching of the greyscale image. The surface defects can now be found using textural analysis, by an edge detector and a threshold level. The increase in processing time is minimal as it is performed whilst the robot is moving to the next position.

The actual time taken to analyse an inspection group is taken as the time to digitise the two images and perform the threshold analysis. The textural analysis can be performed whilst the robot is moving to the next position. The first stage of the analysis takes 0.1 seconds to perform. If a second stage is needed it takes 1 second as the system must wait for the quartz halogen lamp to drop its illumination level.

3.5.2 Polishing

The polishing operation is carried out by following a series of pre-planned paths that are all generated off-line (2). As the paths are planned off-line there must be some consideration of collision avoidance as collissions will undoubtedly occur during the machining cycle. This is a major problem with off-line path generatiion.

The simple approach undertaken is as follows and the implications of it are discussed later in Chapter 8. The surface model of the component allows testing for local collision by creating a simple geometric representation of the robot and for different positions intersecting it with the surface model. It is relatively straight forward to test collision problems for each of the roller position at the surface points but not as simple for moves between points. The trajectory between points cannot be predictd because of the variations in geometry of different castings and so a great many different paths would have to be tested. Instead the polishing path is assumed to be collision free. When the head leaves the surface and during the inspection cycle the system must ensure that the robot is clear of the component whilst it moves between groups. This is accomplished by using a mathematical safe surface around the object. The robot can freely move to this surface from a group and around it surface with out fear of collision. Regardless of the type of path planning all motions are point to point. The different types of paths fall into three distinct sections.

i) Moving around the mathematical safe surface which does not require the adaptive control system.
ii) Moving down from the safe surface to one of the polishing groups. This move proceeds until the feedback determines that the cut is at the required severity.
iii) A polishing move around the surface of the component when the abrasive head must be constantly in contact with the surface.

The first two cases require information on current and goal positions, and in the second case the feedback signal monitoring the cut. In the third case the positional and feedback information is complemented by a knowledge of the component geometry at the point of contact. The robot then knows in what direction the arm must move in order to maintain a constant severity of cut. This vector is defined in a simple form as the surface normal of the goal position and has to be derived off line. It is considered as a small path that the robot can move along in either a positive or negative direction into or away from the surface.

3.5.3 Local path planning for polishing

To polish the surface the robot moves randomly around the path defined by the surface points and their associated links. The path will start from the safe surface or an adjacent group so the first point is either the centre of the group or a bridging point. The robot will move from one point to another selecting the next point randomly from the list of unvisited link points. If all of the link points have been already been visited then the nearest unvisited point is used. When all of the surface points have been visited the robot moves by the shortest route to the exit point which will either be the next adjacent group to polish or to the safe surface. To visit all of the points the path may have to move to the same same point twice.

3.5.4 Global path planning for polishing and inspection

A complete machining of a component requires the robot to first polish every group on the surface. The component is then inspected and any group that fails is marked for a second polish. The robot then re-polishes each of the failed groups. The cycle of inspection and polishing the groups continues until all the groups pass the inspection or a component is deemed to have a very severe defect.

The decision of which group is to be inspected or polished must be simple and easy to calculate. The choice is made by considering the nearest group in terms of the motor coordinate system. The adjacent groups for each group are stored in the data base. By taking the centre of the group for polishing or the position of the camera for inspection, the nearest group can quickly be found. If none of the neighbours are free, i.e. they have already been polished or inspected, then the nearest free group is used. The distance is taken as the root mean square of the difference of the two seven element coordinate vectors.

If a group that is being polished has no free adjacent groups then the system must move to the safe surface before it can polish the next group. This is to prevent collision by the robot and regions on the surface being polished more than once.

3.5.5 Overall On-line Control

The computational load is spread between the three processors in order to maximise the efficiency of the system. The tasks can be broadly divided between the processors as follows:

i) The bottom processor controls the movement of the robot;
ii) The middle processor deals with the inspection and as it is idle during polishing it plans the local polishing path for each group; and,
iii) The top selects which groups are to be polished or

inspected and reads the coordinates from the database.

The bottom processor which controls movement is sent a set of seven element motor coordinate vector data. This set is termed a path. It will enable the robot to reach and inspect or polish a group. To prevent the robot dwelling whilst it is waiting for the next move the next path is read into the bottom processor whilst the robot is moving around the current path.

The selection of the next group and its path differ between inspection and polishing. For inspecting, only the current group and the next group need to be known, whilst for polishing the current group and the next four are planned in advance. This is so that tasks can be shared between the processors. The groups are referred to as LAST, POLISH, READ, PLAN and FUTURE where POLISH is the current group being polished and LAST was the previous. The groups are considered as being in a queue and index one position as a group is completed and a new one added.

The alogrithm ensures that there are no delays between sending data to the bottom processor so the robot is continually moving around the surface of the component.

3.6 Modifications

The early commissioning test upon the basic system identified a variety of hardware and software problems. Some of these problems had to be removed as they severely limited the performance of the system. The author undertook a period of work modifying the system in order to enable further research to progress.

3.6.1 Robot hardware

As already stated the gear boxes attached to the stepper motors had developed a backlash problem. The backlash was so severe that problems were anticipated with the adaptive control system due to the delay in redirecting the motion of the abrasive head.

The boxes were originally chosen for their compactness but on examination of the gear wheels it was found their life curves were far below that required. New harder epicyclic spur gears were obtained and boxes were built for all of the linear and pitch motions. The backlash dropped to 4-8 steps, below the levels that were initially obtained from the old gear boxes .

The rotary motions had high reductions (20:1 and 25:1) and were unsuitable for standard gear trains given the size and weight constraints. Instead harmonic drives were used. The drive system gives a compact reduction which has a backlash of 9 minutes on the output shaft. The gear sets are made in ratios of 80:1 to 320:1 so a 80:1 set was used for all axis with the drive card set to full stepping (200 steps/rev).This has an undesirable effect on the axis velocity dropping the theoretical maximum speed to 50-60 % of the previous level. As no other suitable configuration could be found this drop in performance had to be accepted.

The stiction problem on axis 2 was reduced by fitting O-rings around the nylon rollers that support the arm. This reduced the friction between the two surfaces and give a degree of compliance to the work head.

3.6.2 Software

Modifications were made to the software that was used to generate the triangulated model. The program that created the initial lattice linked from the internal vertices to the nearest nodes on the boundary this results in gaps in the mesh that have to be filled. The gaps need between one and six links on a typical component to generate the mesh. Each case requires a different algorithm in order to select where the links go. If the linking is made from the boundary to the internal nodes the gaps, only two cases result (fig 3.20). One where there is no need for a link, and one where there is need for a single link.

The triangulation has two problems, only the first was corrected. In most cases the structure can be improved by the swapping of links as opposed to moving the links about (fig 3.15). By increasing the tolerances on swapping of oversized or undersized links the triangulation obtains better results and this has been implemented.

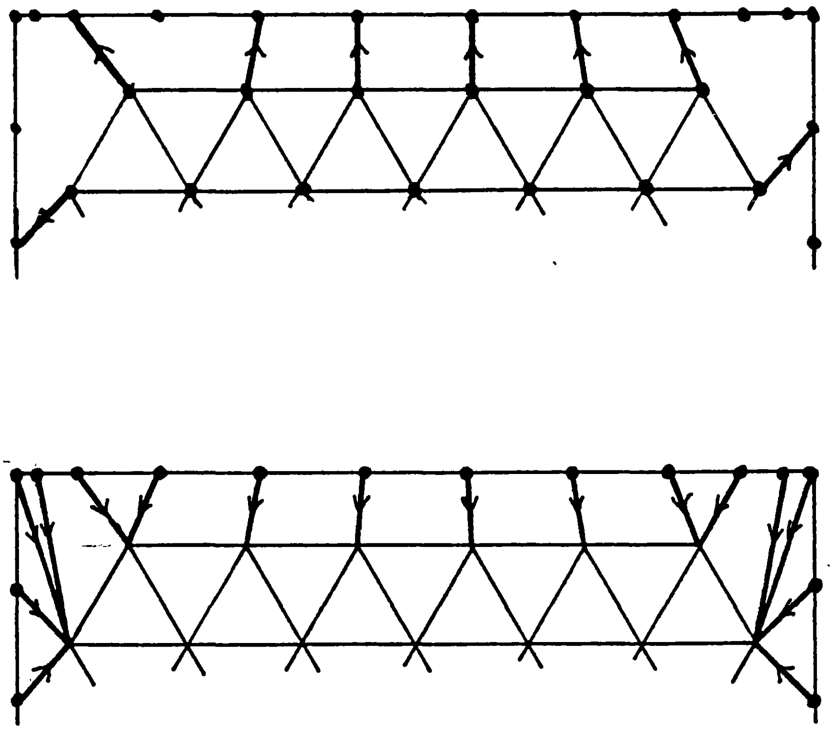


Figure 3.20 Modification to Lattice Generration
The second problem is with the way the triangulation optimises

the position of a node. The new position is derived by an iterative search. A coarse square grid is laid around the node in a XY plane (fig 3.13), and the set points on the grid are tested until the best position is found. A new finer grid is laid at this point and the new set of points is tested. This continues until the distance between the current and the best points fall within a given tolerance.

As the optimisation works in the XY plane steep sided sections of the component take a long time to be analysed and are prone to errors if the points is close to the surrounding polygon boundary. It is proposed that the optimisation should be performed in the plane nearest to the that of the surrounding polygon.

3.7 Concluding Remarks

Due to the limitations with existing commercial robots an in-house robot system was designed and built. The robot incorporates separate abrasive and inspection systems an is controlled on-line by three micro-processors. On commissioning some limitations were found with the drive systems, these had to be removed before work could progress.

A path planning strategy has been formed using data from a triangulated surface model of the component. Off-line the component is broken down into regions for inspection and machining purposes, and then all data is converted to the robot coordinate system for on-line control.

The work performed by other members of the research team included development of the machine vision, and component modelling, and the derivation of a control strategy based upon dividing the component surface into regions for localised inspection and scurfing. To enable the robot device to be fully commissioned the author undertook the development of the basic motion software and the the adaptive control system and this work is described in the next two chapters.

4. CONTROLLING THE GRINDING PROCESS

To perform the scurfing operation the robot must positions the component against the abrasive belt and then move the belt around the surface. It achieves this by calculating a set of points from the surface model and a series of links between the points. The robot can then cover the surface by moving from point to point along the defined links. The points will not be accurate as there will be differences between the generated computer model and the actual component, due to variations in the casting size, previous machining, inaccuracies in the model, and robot positional errors. Also over short distances the robot uses straight line interpolation to move whilst the surface of the component is highly curved. In order for the polishing head to stay continually in contact with the component and thus remove a uniform cut, the grinding process must be monitored and used to control the position of the abrasive belt. This type of control is normally referred to as Adaptive Control (AC).

A simple control strategy was used involving:

i) Continuous measurement of the cutting intensity;
ii) Comparison of the intensity against pre-stored acceptable levels; and,
iii) Modifying the intensity by moving the abrasive belt along the surface normal at the point of contact.

The AC system is to be incorporated within the processor that controls robot movement. An important point to note is that this processor works in the robot coordinate system and has no knowledge of the geometry of the component. The AC must therefore work independent of the orientation and position of the robot.

This chapter describes the development of the measuring system for the adaptive control of the grinding process. The chapter first reviews different methods for monitoring the abrasive process, and discusses the results of some preliminary experiments. It then details the development of a chosen system based upon vibration monitoring. For completeness it includes discussions on the early work performed by W. Wright (46) investigating the monitoring of belt tension and speed, and a series of tests on vibration measurement

4.1 Review of Methods for Controlling Abrasive Machining

The simplest method of adapting compliantly with a surface when machining, is through the use of rubber mountings or pneumatic springs. This has been employed successfully in deburring operations, maintaining a constant force between the tool and the workpiece (26,32). This simple approach is not suitable for this project because the grinding force cannot be varied for different configurations. The system maintains the same force regardless of the contact area and will excessively grind the edges of components. Instead the grinding process must be monitored.

The relationships between state variables of the grinding process has been the subject of extensive research (47,48). An investigation by Marshall and Shaw (49) into surface grinding used a dynamometer to measure the normal and tangential forces, and examined their relationship to wheel speed, and depth and direction of cut. They concluded that normal and tangential grinding forces were inversely proportional to wheel speed and proportional to depth of cut and table speed.

Belt grinding was examined by Mitrevich (50) using a surface grinder. The normal and tangential forces were found to be inversely proportional to belt speed, and belt tension was found to be an important factor with increased tension causing greater grinding forces and metal removal rates.

These analysis show that the grinding process can be measured through monitoring the grinding forces or the belt speed or tension.

4.1.1 Measuring the Grinding Forces.

Grinding forces have been directly measured when trying to optimise CNC cylindrical and surface grinders (39). The forces are usually monitored by strain gauges or piezo-electric devices mounted in either the work holder or the grinder. An experimental system developed for CNC cylindrical grinders used load washers to monitor the forces (41). The results were analysed and processed by an Adaptive Control Algorithm which could be placed in either the CNC system or on a separate micro-computer. The wheel speed, wheel feedrate, work speed, and work dressing rate are controlled to ensure the optimum grinding conditions and the desired surface finish.

Force sensors have been used in robotic grinding applications. The French 'carding' robot (33) uses a separate servo system to position the grinding head. The servo system constrains the grinder so that it can only move linearly. Strain gauges mounted along the axis of the tool measure the compression in the grinder. They measure only the axial forces in the tool and as this is aligned with the component surface normal the normal grinding force is obtained. The position of the grinder is altered by comparing the output from the strain gauges against a preset level that has been programmed by the operator. A set of coordinates are taught around the profile and at each point a grinding level is calculated and stored. The robot then interpolates between the points maintaining the cutting force.

The project at Stuttgart for bathroom fittings (32) uses a force sensor to measure the normal and tangential grinding forces. The robot holds the component in a gripper and strain gauges are mounted along one axis. The component is held against a fixed compliant roller over which runs an abrasive belt. The operator teaches two positions to the robot and the component is orientated normally to the wheel. When grinding, the robot interpolates between the two points. From the knowledge of the orientation of the component relative to the direction of movement of the robot, the measured force can be transformed to obtain the tangential and normal forces The transformation is easily determined within the robot controller from the robot position and orientation.

In the above projects the direction of force measurement is either aligned with the normal force or enough information is known about the system so that the force can be resolved. With the three separate workheads the component can assume any orientation about the contact roller, so the cutting force will not necessarily be along the axis of the abrasive or the work head. Additionally the

Bottom processor which controls the AC system has no knowledge of the relative orientations as it works solely in robot step coordinates. The direction could be obtained by transforming the contact point back to the world coordinates system, but this would place too great a computational overhead on the controlling processor. Also each time the robot moves the transform has to be recalculated.

Clearly the system cannot use direct force measurement without knowing the component orientation, therefore a method of measurement must be found that is orientation independent.

4.1.2 Belt Tension.

In grinding, the belt tension is proportional to the cutting forces (50) and this is independent of the direction of the belt to the component. A system was developed to measure the belt tension on the robot. The belt tensioned is guided by passing it over a series of jockey wheels. Strain gauges are mounted on one of the supports to measure the radial loads on the spindle due to changes in the belt tension (fig 4.1).

The resulting signal was found to be very noisy and non linear with the observed metal removal rate. The main problems appeared to be flapping and rippling of the belt over its unsupported regions, which caused variations in the belt tension. Due to the lack of stiffness in the robot, vibrations caused by inertia effects were also transmitted directly to the strain gauges. A spring loaded jockey wheel was introduced to reduce the fluctuations by maintaining a constant contact between the guide roller and the belt but this had little effect on the strain gauge signal.

4.1.3 Belt speed.

When the abarasive belt was grinding, the resulting tangential force loaded the drive system, and caused variations in the belt speed. Through monitoring a measure of the force was obtained. The speed of the wheel was measured using a magnetic pick-up detecting a set of steel studs mounted within the aluminium drive wheel.

Using the air motor as the prime mover there was little

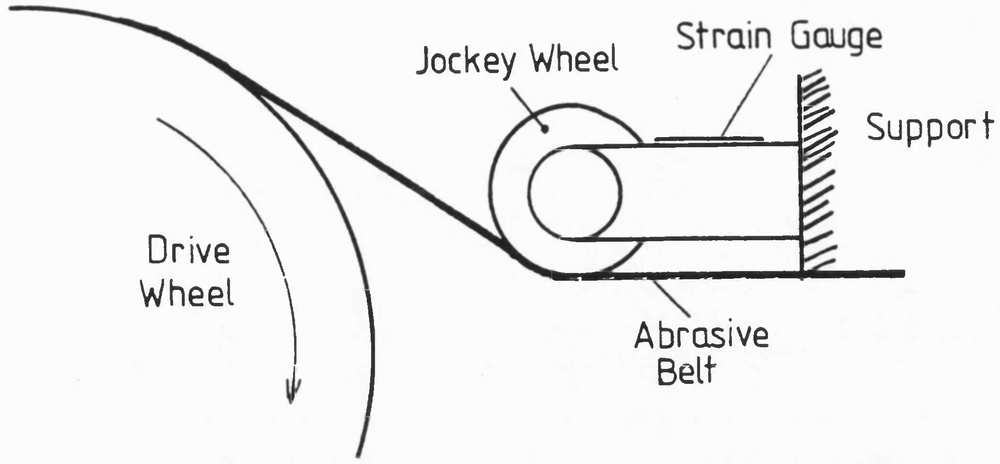


Figure 4.1 **Belt Tension Measurement**

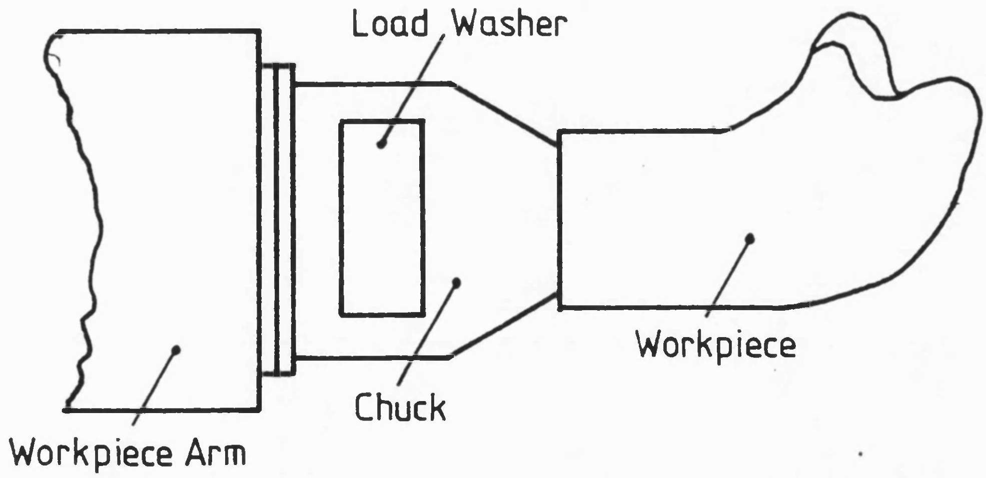


Figure 4.2 **Installation of Load Washer within Chuck**

difference in speed fluctuation for the grinding and the non-grinding states. An electric motor of lower power (80 W) was substituted to increase the effect of the grinding forces on the belt speed. It was soon apparent that the grinding forces are small, and for there to be significant measurable changes in the belt speed the motor would have to be very low power. When subjected to dynamic conditions the sudden loading of the system caused the motor to stall. A subsequent static test off the robot showed that a normal force of two to three Newtons was sufficient for adequate grinding.

4.1.4 Motor power.

A combination of the above two methods was tested through the monitoring of the motor power. This method has been used in the controlling of a fettling robot at the IPA in Stuttgart (26,42). The signal has also been suggested for fail safe routines as well as cutting depth control. It was felt that if the electric motor was used a simple signal could be directly obtained and by the use of suitable processing a reliable measurement obtained.

Using the electric motor to drive the abrasive belt, the power input was measured by placing a resistor in series and measuring the voltage drop across it. The signal was filtered to produce a steady signal using a second order low pass filter with a cut off of 60 Hz. The system responded well with steady loads but with a rapidly changing load inertial affects caused the system to lag.

The moving parts of the system were lightened and a more powerful electric motor (120 W) was substituted. The lag in the system dropped but a reduced signal occurred. The same problem occurred as with the belt speed monitoring, the differece between the grinding and non-grinding is easily detected, but to obtain a significant change in the signal that relate to different grinding intensities is very difficult, especially when compared to the background noise. To obtain a signal the motor had to be very low in power which resulted in the system stalling under some grinding conditions.

4.1.5 Acoustic/Vibration.

A method that has been proposed for AC is the in-process monitoring of the high frequency signal that a component emits as it undergoes stress, as occurs with chip forming (51,52). The process is commonly known as Continuous Acoustic Emmission (CAE) and occurs within analyses the high frequency non-audible band between 40 and 60 KHz. It has been used to monitor the tool wear and fracture in turning operations (53,54), and has been proposed as a method for control of grinding by Roberts and Wilson (43,55). It has recently shown promise as a method of identifying burning in cam shafts and monitoring tool wear on CNC surface grinders (43,56).

When considering CAE it had been noted during testing, that there was an audible change between the grinding and the non-grinding states. This is obviously not CAE but through observations appeared to be a reliable indication of the current cutting state. As the audible band is of lower frequency (up to 14 KHz.), it was decided to investigate this audible range first. The sound occurs from structural vibrations induced by the grinding operation. The signal can therefore be measured by monitoring either the airborne or the structural vibrations.

A simple test was performed on the higher frequency structural vibration through mounting a piezo-electric accelerometer upon the workpiece arm, just behind the chuck. The accelerometer measured only the axial vibrations in the system whilst the component was excited with a radial load. The resulting signal was a high frequency complex wave form. To remove any d.c. components and vibrations caused by the stepper motors moving the robot, the signal below 1 KHz was filtered out. It was noted that as the cutting force increased a similar increase in the amplitude of the waveform was observed. This method appeared more promising than the other ideas and so further analysis of the process and the resulting signal were undertaken.

4.2 Analysis of the Vibration Signal

From the previous simple test a relationship had been established between the grinding intensity and the structural vibrations. It was proposed that further measurement of the structural vibrations should be made by mounting a Kistler piezo-electric load washer in the chuck between the component and the work head (fig 4.2). The relationships between the normal grinding force and the following variables could be established:

i) Amplitude of vibration;
ii) Variations in the distance of the point of contact to the load washer;
iii) Compliance of the contact roller; and,
iv) Direction of applied force.

The effect of variations in the components geometry upon vibration amplitude was also considered.

The series of controlled experiments were performed (46) away from the robot using a similar belt grinding system. The test rig was more rigid and an identical mounting system was used. The washer measures the axial forces in the system and not the radial ones. A force applied laterally will affect the signal as there is a moment arm but this is reduced through using slip washers. The normal force can be precisely controlled as the abrasive head runs upon a linear bearing and is applied by weights acting over a pulley giving a variable load of between 0 and 5 N. The drive system used was a variable speed AC motor.

A piezo-electric load washer (Kistler Type 9031) with a frequency response of 80 KHz was mounted to detect the axial loads and vibrations in the component. This was connected to a charge amplifier (Kistler 5001) producing a measurable output in the range 0-5V for light loads. The output was analysed by a spectrum analyser (Hewlett Packard 3582A). A section of brass bar was mounted in the chuck. The spectrum was then measured for a non-grinding and a grinding state. The tests were performed to analyse the low frequency audible signal, 1-20 KHz., and the possible high frequency CAE 40-60 KHz. Typical rsult are shown in figure 4.3

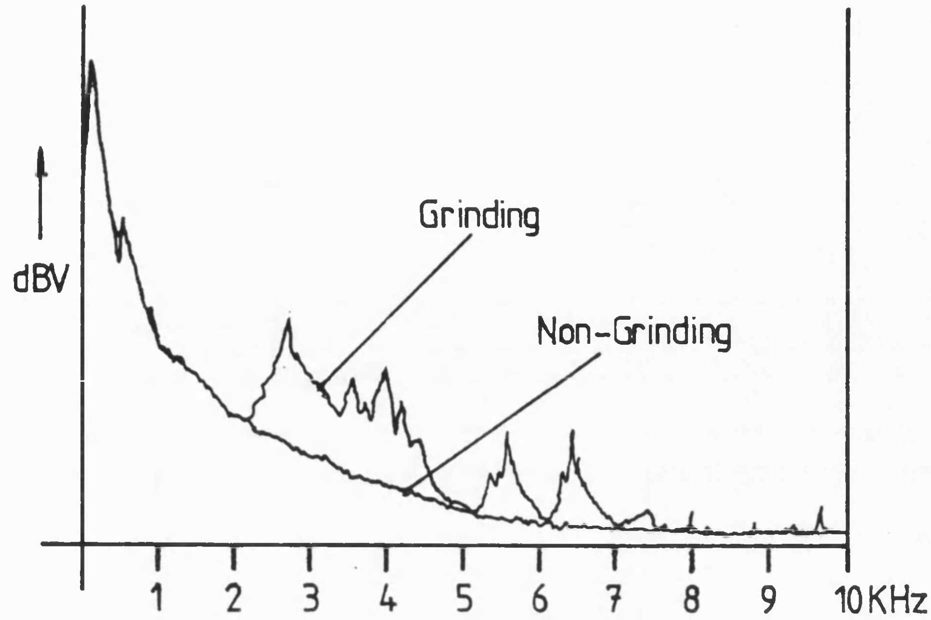


Figure 4.3 Spectra for grinding and non-grinding conditions

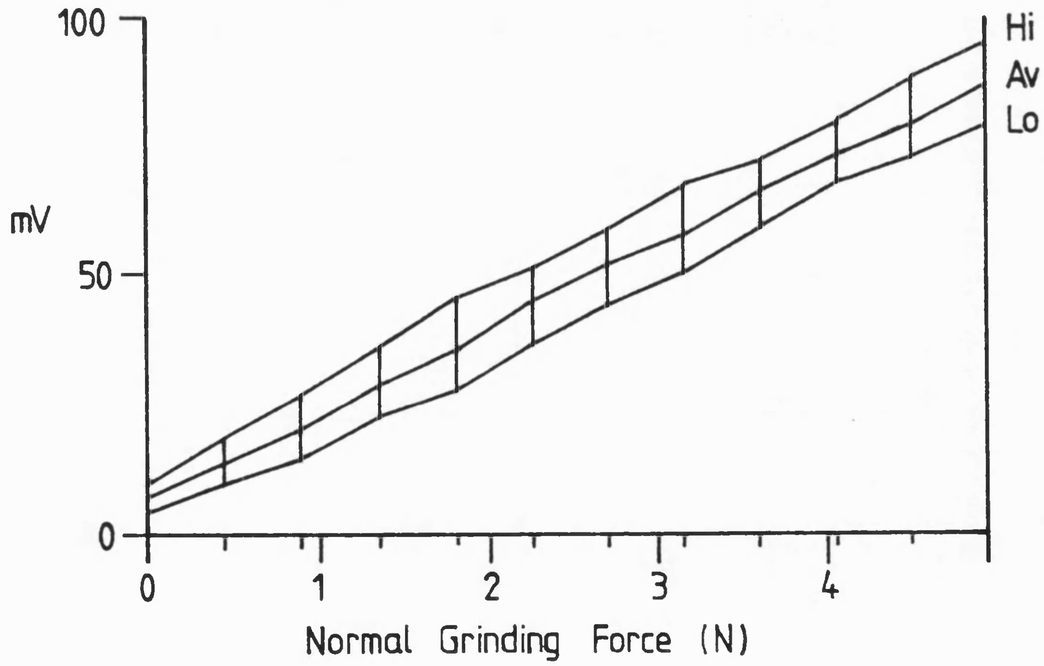


Figure 4.4 Force against RMS of Vibration Signal

When the tests were performed to evaluate the vibration feedback the signal was seen to fluctuate . To assist in the logging of data an intelligent multimeter (Thurby 1905a) was used that would continually measure the signal and store the values over a 30 second sample period. All the values could then be analysed and the multimeter used to give the average, highest, and lowest readings. (fig 4.4)

4.2.1 Induced Vibrations

The low frequency signal was considered first. The signal was believed to be caused by the component resonating as it was machined. The frequencies coinciding with the theoretical modal fequencies of a cylinder. The resonant frequencies of the component were confirmed by exciting the component by a vibrator and sweeping the frequency band. On comparing this signal to the one obtained from the spectrum analyser, the resonant frequencies were found to coincide with the major peaks for the grinding signal between 2 and 20 Khz.

In order to understand the relationship between the signal amplitude and the grinding, the cause of the resonance must be established. It could occur from abrasive particles striking the component at a resonant frequency. This was tested by varying the belt speed. The resonant peaks still occurred but as the belt speed dropped a linear reduction in amplitude was noted. This suggests that the frequency of the vibrations are not caused by the particle striking rate, but instead, each individual particle excites the system and the more particles that strike the object the greater is the total sum of the vibration.

A component will resonate only if it is excited at a resonant frequency or by an infinite spectrum. A common method of finding the resonant frequencies of an object is to strike it with a sharp blow and monitor the component with a spectrum analyser (54). The blow excites the object with an infinite spectrum (white noise) and the resonant frequencies are easily detected. A similar occurrence is believed to happen with the grinding. Each individual particle acts like a tiny blow and the more particles that strike the greater the total force is. For the rest of the thesis the signal will be referred to as the resonant signal.

After performing the various tests the following relationships were established:

i) The root mean square (r.m.s.) of the forced vibrations were found to be proportional to the grinding force. This corresponds with the idea of resonance, as the amplitude of individual excitation will be proportional to the force. All further tests were considered against the r.m.s. of the entire spectrum.

ii) The r.m.s increases linearly as the point of excitation moves away from the load washer. Three points on the cylinder were excited resulting in curves (fig 4.5). The excitation at each point is constant but the moment arm increases giving a higher axial load. The force increases linearly with the distance from the load washer. The figure has been drawn to show the shape of the different curves, the actual levels only varying by 10 % between the three positions

iii) The r.m.s. varies with the contact area of the belt. This was altered by changing the angle of incidence of the roller to the component, and as there is low roller compliance the contact area changes This is predicted from the idea of individual impulses from the grit particles. If there is better conformity there will be more particles in contact and therefore more excitation.

iv) The direction of the applied force had no affect upon the signal for the same conformity.

v) Different components produced different frequency spectra, but in each case the r.m.s value of the signal behaved in the same linear way.

4.2.2 Continuous Acoustic Emission

The signal from CAE is defined as 'The class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localised sources within a material or the elastic wave(s) so generated' (58). It is thought that this occurs due to a

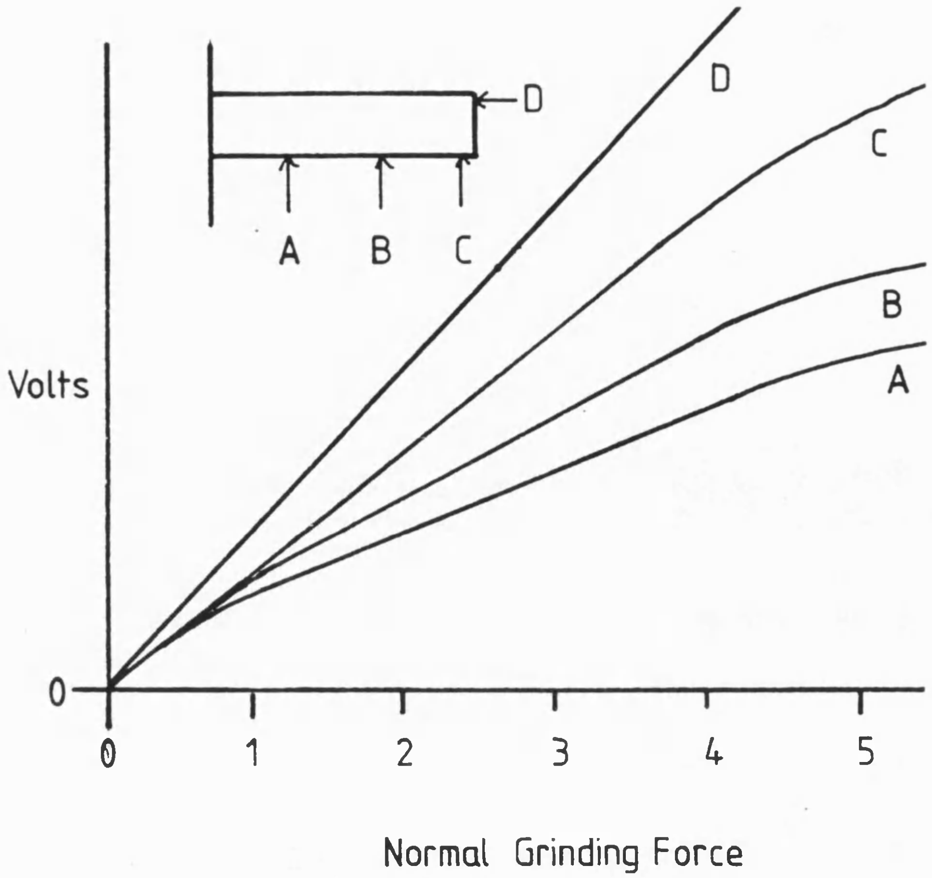


Figure 4.5 Vibration Signal at Different Contact Points

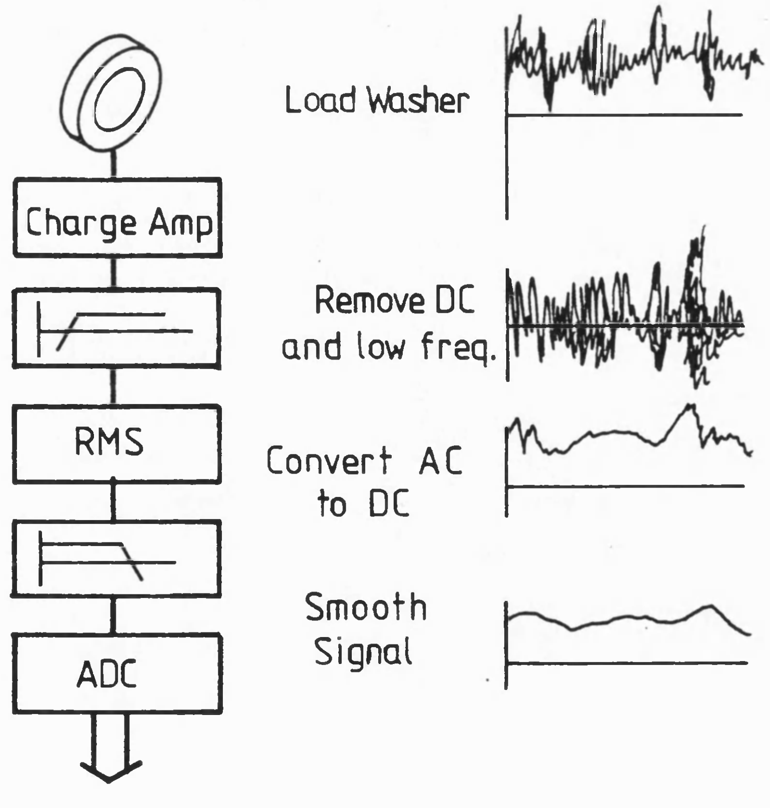


Figure 4.6 Block Diagram of Vibration Signal Processing

number of mechanisms including fracture, plastic deformation, rubbing and temperature dependant phase transformations.

A linear relationship between chip formation and the CAE energy rate wasderied b Roberts (43). A relationship for the cutting forces is obtained from a derivation of chip length for external and internal grinding such that :

root mean square (r.m.s) of the output = K * /(normal force),

where K is a constant for a given grinding belt/work combination, depending on the arrangement used. A contact roller is analogous to an external grinding operation.

From testing the following relationships were established:

i) The signal follows the theoretical relationship.
ii) The CAE signal amplitude is considerably lower than the resonant signal, approximately one tenth.
iii) CAE is dependent on the belt-workpiece conformity. Variations in the conformity would change the rate of chip formation and so increase the signal. This is confirmed by Wilson (55).
iv) CAE is independent of the distance to the load washer. The position of contact relative to the sensor should not be affected if the sensor is measuring the energy produced by the grinding and this seems to be confirmed.
v) By altering the direction of the applied force to the load washer, the CAE did not alter significantly.
vi) There was no variation in the signal between different shaped components for the same conformity.

All of the results follow the theoretical idea of the CAE being a measure of the metal removal rate, and not a function of the machining geometry.

4.2.3 Discussion

Both of the signals appear to provide a sensible basis for the development of the force feedback, both having a simple relationship compared to cutting intensity. For the AC system the resonant analysis was selected for the following reasons.

i) The resonant signal is considerably larger in amplitude and was thought to be less susceptible to errors caused by noise and shock inputs generated by the movement of the robot.
ii) The measured frequency band is lower, hence reducing problems with circuit and filter design.
iii) It has a linear relationship with cutting force, although the CAE signal can be made linear by squaring the output.
iv) The variations in signal level as the point of excitations moves away from the washer, are small and are easily compensated for.

To ensure a uniform analysis of the signal the conformity between the belt and the workpiece must be maximised at all times. To control the process, two threshold values are set to mark the range of acceptable grinding conditions. These values are determined experimentally at two points on the component, one close to the chuck and one further away. All levels between can be obtained by interpolating between the two values.

The CAE signal is between 40 and 60 Khz. and is considerably smaller than the resonant signal, behaving in a similar way. Therefore it was not felt necessary to remove this frequency band from the load washer output.

4.3 Circuit design and computer interface

The analysed signal must be interfaced to the controlling Bottom processor. It will be connected via one of the parallel ports. A simple electronic circuit was designed and built that would analyse the signal and extract the r.m.s value and then present it digitally to the controlling processor.

4.3.1 Specification of the circuit.

The output of the charge amplifier is typically between 0 and 100 mV. when the system is operating at the required cutting conditions. It is initially filtered by a high pass filter with a cut off frequency of 2 kHz. An amplification stage may also be include.

During tests the root mean square of the signal was used as the measure of cutting intensity. A similar conversion must be performed on the filtered signal. The rectified signal was sampled by the controlling processor, and had a high frequency (greater than 3 KHz.). The sampling is liable to be relatively slow (1 KHz.) so the signal must be smoothed to prevent aliasing.

Finally the computer is digital so an ADC must be used. A block diagram of the whole system is shown in figure 4.6

4.3.2 Data logging and computer interface.

The active stages of the circuit were designed with spare stages in case further filtering was needed. All active stages were designed around 741S Operational amplifiers (Op-amps) which have a full power bandwidth of 200 KHz. The input from the charge amplifier were buffered through an Op-amp stage to give low impedance to the filters. The high pass filter was constructed as a second order Butterworth, with a variable cut off frequency of 0.9 to 4.0 KHz. An amplification stage was also included with a gain of between 5 and 50 that gave an output signal of 0-5 V.

An AD536A RMS to DC convertor was used to rectify the signal. This IC convertor operates up to 2 MHz. The device has a gain adjustment and is internally protected against high input signals and output short circuits. The IC produces an output of 0-10 V.

A Radio Spare 427 8 bit successive approximation ADC was used to convert the signal. This IC set in unipolar mode gave a full reading for the full scale deflection of the RMS/DC convertor. The clock frequency of the IC is set externally at 800 KHz. giving a convertion time of 12 us. The external clock is demodulated from a 3.2 MHz quartz crystal using frequency dividers. The start of conversion signal was controlled by the clock signal and required external setting. The output from the ADC was buffered via an 8 bit 74 TTL series tri state buffer which was controlled from the end of the conversion signal from the ADC.

Software control of the feedback is relatively simple. The output from the ADC is connected to the high byte of the port A of the DRV11J in the bottom processor. The start of the conversion signal is connected to the msb bit of port B. Data is logged by setting the msb signal high which starts the convertion of the ADC. The internal logic of the circuit is reset by the rising edge and at the middle of the next clock signal the start of conversion signal is set on the ADC. After 12 us the result can be read back via port B. The 8 bit ADC gives a value from 0-255 where 0 is not grinding.

4.4 Optimising the feedback.

The grinding intensity must be measured after each movement of the robot i.e. after the stepper motors have moved. At this point a decision is made if the cutting is currently too hard or soft. It is propossed that two levels are used that measure the range of acceptable cutting conditions. The level is sampled and if the signal is within the tolerances then no change will be made to the cutting intensity, otherwise it can be altered by moving the abrasive head into or away from the surface, thereby increasing or decreasing the normal force. The range of levels were found to vary slightly between components and were therefore obtained experimentally. On a component it would not be possible to measure every point upon the surface and obtain the correct tolerances. Instead a series of points were tested and the levels for the entire component are calculated using a linear function of distance from the load washer.

The state can be sampled after every step but the time interval between samples will vary as different motors operate at different speeds. As has already been stated, during the test the signal was analysed by taking an average value of the r.m.s over a 30 second sample period due to the high frequency nature of the signal. In the robot system could only be sampled at the movement stepping rate of 100 to 200 times per second. To smooth the signal and to prevent

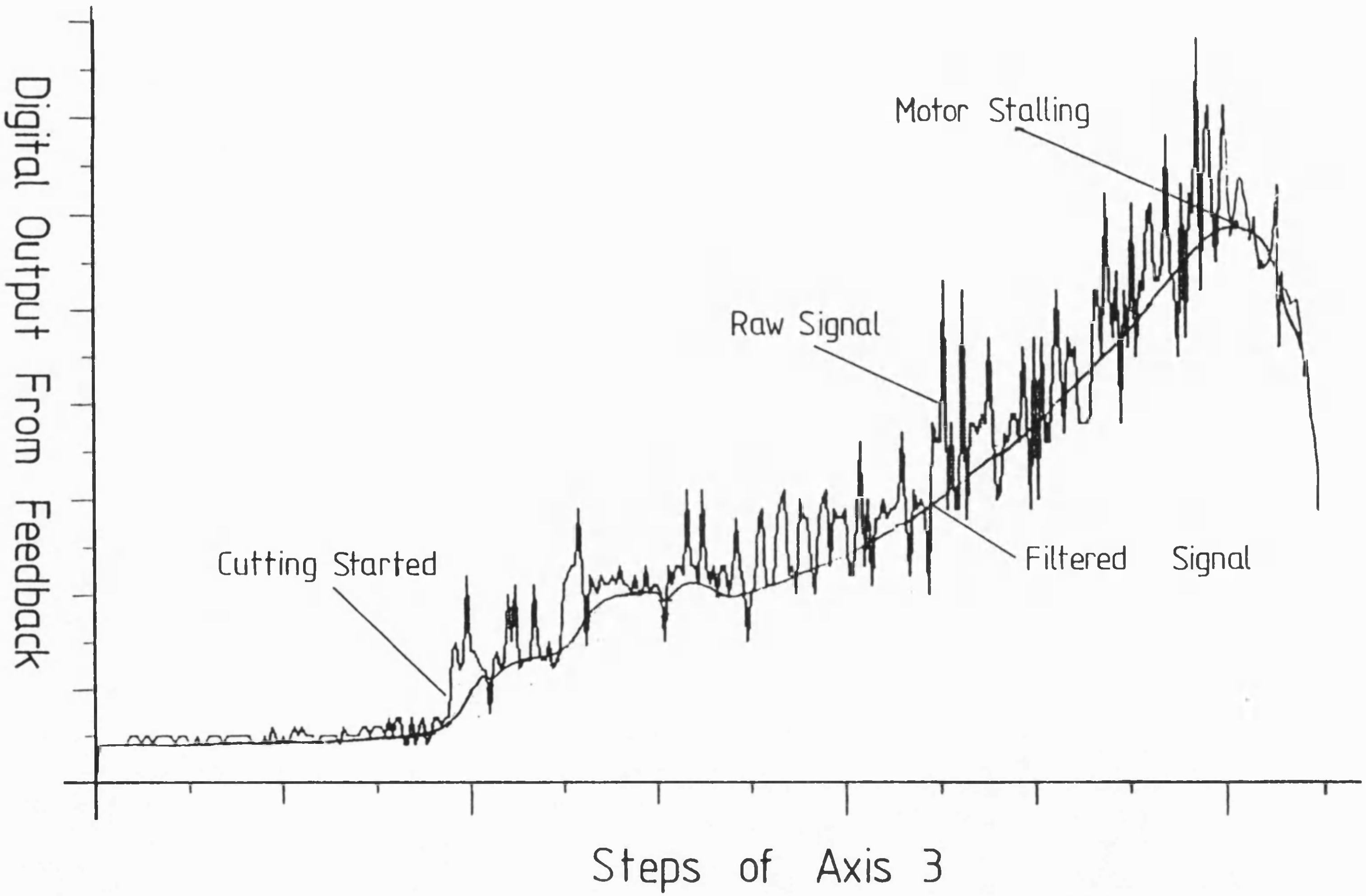


Figure 4.7 Feedback Signal v Steps

aliasing of the signal, the output from the RMS/DC convertor is processed by a low pass filter. The optimum values were determined from tests on the robot

4.4.1 Tests on vibration feedback

By moving axis 3 forward (fig 3.1) and sampling the output signal after each step the relationship between the cutting force and the robot movement was examined. The signal resulting from initial belt contact and increased grinding intensity can be seen in figure 4.7. A change is shown between the cutting and non-cutting conditions and the level falls off as the motor begins to stall. There is also a large oscillation about the average signal level.

By changing the cut off frequency of the low pass filter the signal can be smoothed (fig 4.7). If all of the oscillation is removed the filter is operating at around 8-12 Hz. Through comparing this signal with the original, the point at which the cutting is detected moves because of the time delay introduced. The robot can move 10 to 20 steps before the change in signal is noted. A better method of analysis is to consider the feedback not in the time domain but in terms of the robot movement i.e. using the motor steps.

4.4.2 Running Average

The controlling processor is the only device that can analyse the signal in terms of robot steps. The analysis must be quick and simple in computing terms, so as not to delay the motor control. A simple form of digital filtering is needed.

The average signal from the static tests behaves linearly compared to the grinding force. A running average operating on the signal will remove most of the variations. The running average is performed by taking the current signal level as the sum of the last n samples. This is simply performed by keeping the total of the last n samples and adding a new sample to the total while subtracting the first sample included in the total. The size of n will alter the nature of the filter. The larger n is the greater will be the lag in the system. Experimentally by repeating the previous cutting test

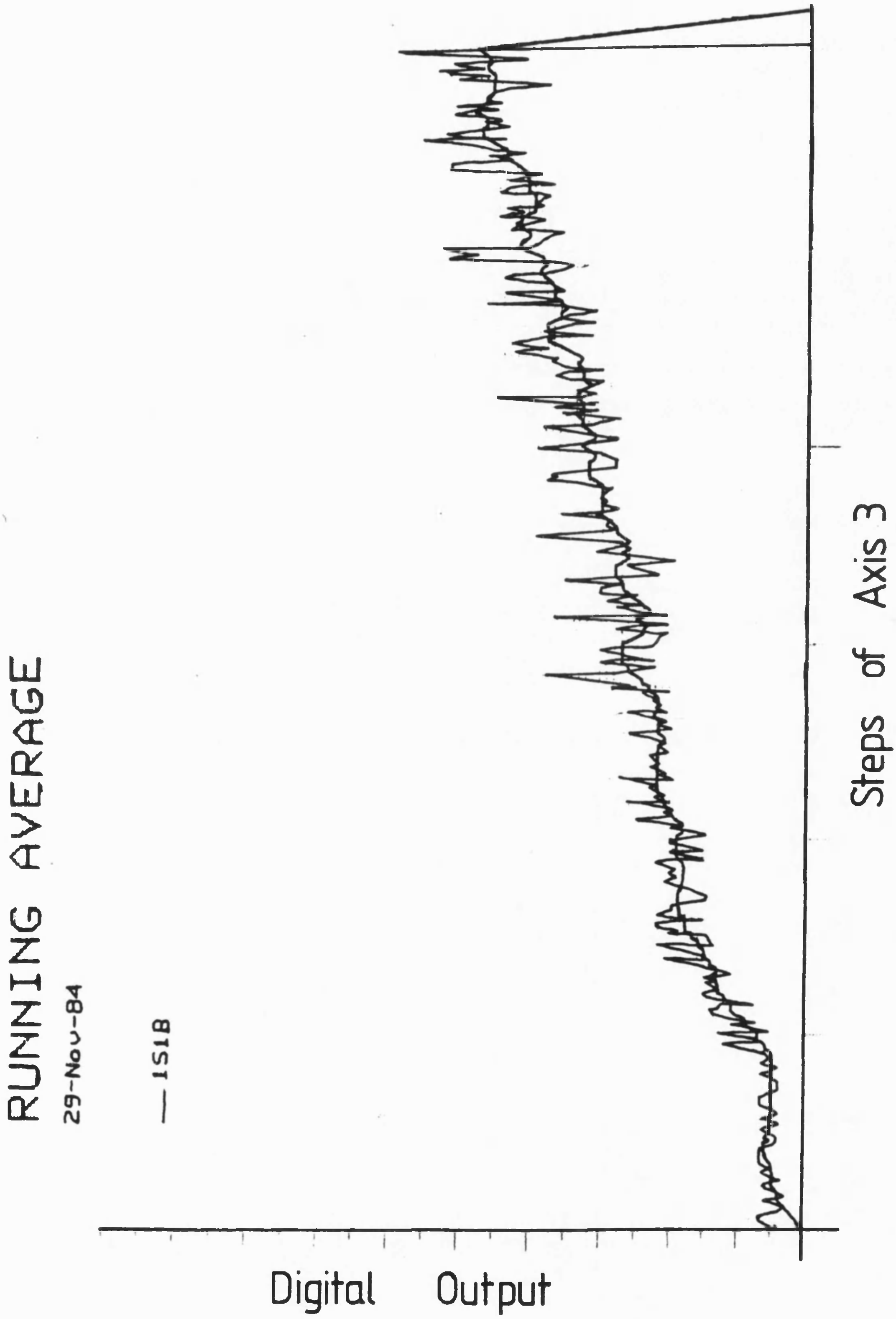


Figure 4.8 Running Average Performed on Vibration Signal

and varying the length of the sample an optimum value was found with n set to 12. The signal can now be seen to be smooth and the detection of the change in cutting signal was not seriously delayed (fig 4.8)

4.5 Concluding remarks

Due to errors between the calculated paths and actual position on the surface a reliable measure of the current cutting conditions is needed to control correctly the scurfing operation. Currently the most popular method for monitoring grinding is through direct force measurement. This is not suitable on the robot as coordinate information is required to transform the measured forces into the direction of the surface normal. Similar methods which monitor belt speed/tension are not effective because of the low level of the cutting forces. Instead a reliable method has been developed that measures resonant vibrations of the component induced by the grinding process.

When the abrasive belt is brought into contact with the component, individual grit particles cause it to resonate. The vibrations are measured by a piezo-electric load washer which is mounted between the component and the work head. The output signal is processed and provides a linear measurment of cutting intensity. Variations in compoent geometry and the distance of the point of contact from the load washer affect the level of the signal but these are easily compensated for by measuring a set of points on the component.

The sensing device is interfaced via a parallel port to the controlling processor and the process is controlled by comparing the measured signal against two preset levels.

Finally before the robot system can be fully commissioned the force sensing device must be incorporated into the whole system. It is an integral part of the basic robot movement software and the deveopment of this is specification and development for this are described in the next chapter.

5.BASIC ROBOT MOTION AND FEEDBACK CONTROL

Before the robot could finally be commissioned, the basic motion control software had to be developed and the scurfing adaptive control system installed upon the BOTTOM processor.

Through examining the process five main requirements were identified:

i) The control of the stepper motors;
ii) Calculation of moves;
iii) Monitoring of the adaptive control;
iv) Communicating with the control processor; and,
v) Path planning.

The initial development of the robot system by S.Jenkins, defines the path planning (sec 3.5), and the structure of the data for communication. This chapter describes the software developed by the author for controlling the other four functions. The program must perform the tasks in real time and is constantly accessing the parallel ports to interface to the robot and the top processor. To obtain the desired fast response, all of the routines were developed using the RT11 macro assembler Macro-11.

All movements are conducted in the motor coordinate system. There is no positional feedback from the robot so all movements are made against a known reference position. As the robot moves the number of steps for each axis relative to the reference point is stored in a register. On start up the robot must be moved to the reference point and the registers zeroed.

To polish or inspect the component the robot moves through a series of defined points that lie either on the surface of the component or are on the safe surface. This sequence of points is referred to as a path.

The path can be made up of three different types of moves.

i) A safe move. From one absolute coordinate to another as in moving around the mathematically safe surface and to an inspection position.

ii) A start move. A move from the safe surface down to one of the polishing groups. This move proceeds until the AC determines that the cut is at the required severity.
iii) A cutter move. A scurfing move with the abrasive head held by the AC in contact with the component. The move is around the points inside a polishing group.

When scurfing the path may start from either a neighbouring or an unconnected polishing group, or from the safe surface. The path may contain both of the first types of move in addition to the cutter move. The bottom processor must distinguish between the different types of moves in order to interface to the AC system.

The bottom processor must also inform the top processor when a path is complete and if any errors have occurred. If an error does occur, or if the operator wishes, the system must be halted without losing its position.

5.1 Control of stepper motors.

Each stepper motor is interfaced to a UDB-053/2 stepping motor drive board. This is a 24 volt, 5 amp., dual angle control board. The board has no internal oscillator and is stepped by means of an external pulse. This is generated by the bottom processor. The direction of rotation is controlled by a separate bit.

The specification of the board includes:

i) The step pulse is active low (from 12 to 0 V.);
ii) The minimum width of the stepping pulse is 50 us.; and,
iii) The direction control can only be changed when the motor is off, i.e. when the step pulse is high.

The seven motors cards are interfaced to the data register of port B of the DRV11-J, buffered by an inverting darlington array, the low byte being used for the step pulses and the high byte for the direction. Binary nought in the data register gives a 12 V. output to the drive card. The motor can then be stepped by setting a bit alternatively to 0 and 1. A positive rotation is set by a 0 in

Axes	Steps of Backlash		Stepping Frequency		
	Old Gearbox	New Gearbox	Without Acceleration	With Acceleration	%Increase
1	15	3	154	175	20.1
2	17	7	96	113	17.5
3	38	4	160	194	21.2
4	22	4	149	198	32.6
5	57	9	100	126	26.0
6	30	11	114	134	17.4
7	25	11	124	140	12.9

Table 5.1 Axes Backlash and Stepping Frequencies

the corresponding bit in the high byte and a negative rotation by a 1. The sequence shown in figure 5.1 shows how axis 3 can be rotated in both directions. As each motor has an independent drive card, motors can be stepped simultaneously.

The stepper motors are Sigma series 20 which can be stepped dependent on the load up to 2 KHz. If there is no ramping of the stepping frequency the maximum for each of the axis before the motors stall or oscillate is below 1 Khz (Table 5.1). This is mainly due to the stiction and inertial loads in each axis at start up. Once the motor is rotating the loads are less. By using a lower stepping frequency initially, and increasing it steadily over 10 to 15 steps the motor can be rotated at a higher frequency.

Motors can be selected by setting the relevant bit in the low order byte of a 16 bit register and setting the directions in the high order byte (fig 5.2). Calling the subroutine 'DRIVER' (see appendix C), will then set the correct directions for each motor and transmit the stepping pulses.

The control program has to perform several different monitoring and data reading tasks whilst it is moving from one position to another. It does this by utilising the delay that occurs between the successive motor step pulses. The step pulse is relatively short compared to its stepping frequency and the time can be utilised for other tasks. The stepping frequency must be not be affected by performing the other tasks. The actual stepping of the motor takes 70 us to set the direction and send out the correct length step pulse. Typically between a delay of 900 to 1000 us. is needed between steps in which all feedback analysis and reading of the movement data must be concluded.

5.2 Movement algorithm

Each axis is moved by setting a step and direction bit on the data register. The relevant motors and directions are selected by knowing the present and goal positions of the robot in motor coordinates. To control the motion the following points have been considered:

Instruction.	Octal	Binary															
1. Clear Register	0,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Set Direction +ve	0,						0										
3. Set Step Bit	4,														1		
4. Reset Step Bit	0,														0		
5. Wait 50 to 1000µs																	
6. Direction -ve	2000						1										
7. Set Step Bit	2004,														1		
8. Reset Step Bit	2000,														0		
9. Clear Direction Bit	0,						0										

Figure 5.1 Data Sequence for Stepping a Motor

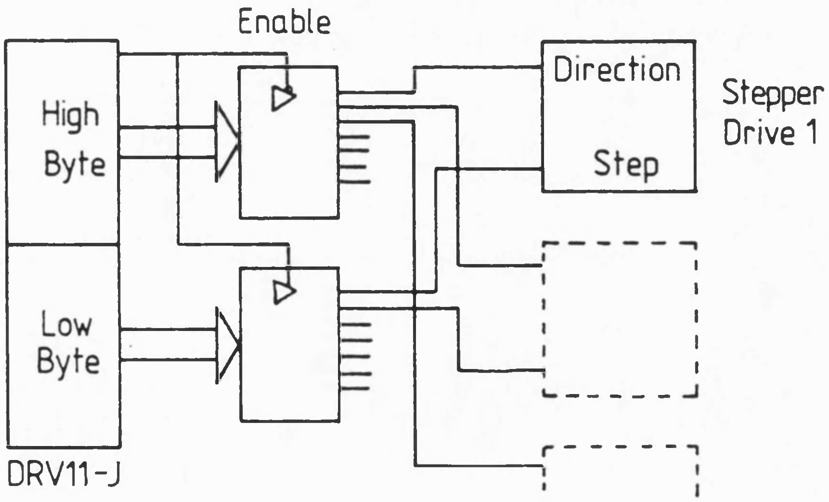


Figure 5.2 Stepper Motor Drive Card Interface

i) The processor has no knowledge of its geometry and therefore the simplest and fastest means of moving between the two points is to be used.
ii) The backlash in each axis (table 5.1) is compensated for when the direction of rotation is reversed.
iii) Every axis has a different configuration and loading, so each motor will have a different maximum speed. The frequency at which the pulses are sent to the stepper motors will depend on which motors are moving, and is ramped in order to obtain maximum speed.

5.2.1 Implementation of movement algorithm

The simplest and quickest means of moving the robot from point to point is to use the Digital Differential Analyser (DDA) technique, which has its origins in machine tool development (59,60). The routine can step two or more motors so that all movement begins and ends simulataneously, regardless of the distance moved by each motor. The steps are timed so each motor is pulsed regularly resulting in a coordinated motion. The general algorithm is shown in figure 5.3. The move for each axis is obtained from the difference in steps between the current position and the goal position.

The delay loop is used to control the stepping frequency of the motors, ensuring that they run at maximum efficiency. To do this the delay is calculated by considering the number of steps of each motor relative to the total move. Additionally each motor has its own constant which is the delay required by the movement algorithm to achieve the maximum stepping rate after ramping. The ratio of steps and the delay constant are multiplied together for each axis and the maximum value is selected as the delay for the move. The calculation is shown in figure 5.4 for the three workhead axes.

The backlash on each axis can be removed by comparing the current axis movement direction with its previous move. If they are different the backlash is added to the absolute value of the move.

The position registers are updated after every step. If the system is halted or aborted during a move, the position registers will hold the current coordinate.

```
For each axis, i = 1,7
  move(i) = relative move of axis i
  dirm(i) = direction of move(i)
  move(i) = |move(i)|
Next axis, i

max = maximum of move
sum(i) = max/2, i = 1,7
```

Main loop

```
For each step, n = 1,max
  For each axis, i = 1,7
    sum(i) = sum(i) - move(i)
    if sum(i) <= 0 then
      sum(i) = sum(i) + max
      step axis 'i' in direction dirm(i)
    end if
    delay to control speed
  Next axis, i
Next step, n
```

Figure 5.3 DDA Algorithm

Taking the following three axis moves

Axis	Move	Delay	Total
1	220	300	66 000
2	150	500	75 000
5	200	420	84 000

Maximum delay is 84 000
Maximum move is 220
$\therefore$ delay used is 373

Figure 5.4 Step Delay Calculation

Axis 5,6 and 7 are all revolute and the position is defined in the positive direction between 0 and 15999 (i.e. 16000 steps per revolution). When moving from position 10 to position 15970 the algorithm would obtain a positive move of 15960 steps, while the quickest move is a negative move of 40 steps. The relative movement of these axes are tested and if greater than half a revolution then the direction of the move is reversed and the absolute move calculated by taking the move away from a full revolution.

The delay period after allowing for the DDA and updating all registers is of the order of 500 us. This period is sufficient to read in information from the top processor and to monitor the feedback.

5.2.2 Zeroing the robot

The robot is zeroed at the reference position on start up and in the absence of positional feedback at regular intervals in the machining cycle.

Each axis has an infra red photo diode mounted on it. As the axis passes through the datum position the beam is broken by a pin. The outputs from the photodiodes are interfaced to the low byte of the data register A. A bit set to 1 signifies that the beam is broken.

To zero the robot, each axis is moved until it breaks this beam. The direction of the movement is obtained by reading the current position register. If it is positive the robot is moved in a negative direction and if negative vice versa. If the axis has moved in a negative direction it is moved past the zero position and then zeroed in the positive direction. This ensures that the axis are consistently zeroed from the same direction removing backlash problems. On start up the direction for the initial zero has to be input by the operator. Afterwards the system will automatically zero the axes in the following sequence 3,6,4,7,1,2, and 5 (fig 3.1), to prevent collisions

Axis 5 contains the load washer which is connected by a cable to the charge amplifier. To prevent the cable becoming tangled the number of revolution of the axis are counted and the axis is rotated to the start position before zeroing.

5.3 The Adaptive Control System

When the robot is moving to a cutter point it must monitor the feedback to ensure that it is within the required tolerances. The tolerances are read down from the top processor and are unique to each surface point. A simple strategy is used to control the process which samples the grinding intensity after each step, via an eight bit ADC, and the signal is compared to the two preset levels. If the cutting intensity is outside the specified tolerances, the robot compensates by moving the abrasive head into or away from the surface. The direction of the move is specified by the surface normal at the goal surface point and is derived off-line. This move will be referred to as the back-off vector for the rest of the thesis.

Fatal errors will occur during the scurfing cycle if the belt breaks or stalls as there will be no input for the vibration feedback. As there will be no vibrations, the monitoring circuit will read a non-cutting state and feed into the component along the backoff vector. The belt speed must be tested for these conditions to prevent damage to the robot or the component.

5.3.1 Type of move

A surface point can be specified as either a start or a cutter move. This can easily be determined from the previous move. A start move is when the robot moves down from the safe surface and therefore must be the first cutter move after a safe move (fig 5.5). The feedback responds in different ways to the different moves.

On a safe move the arm is to move until it reaches the desired machining level. During the move the processor does not respond if the feedback level is too low, only when the feedback level goes above the high tolerance. It then ends the cutter move at this position. If the robot reaches the goal position without exceeding the high tolerance the current feedback level is compared with the low tolerance. If the level is too low the arm moves in the direction specified by the backoff vector until the desired

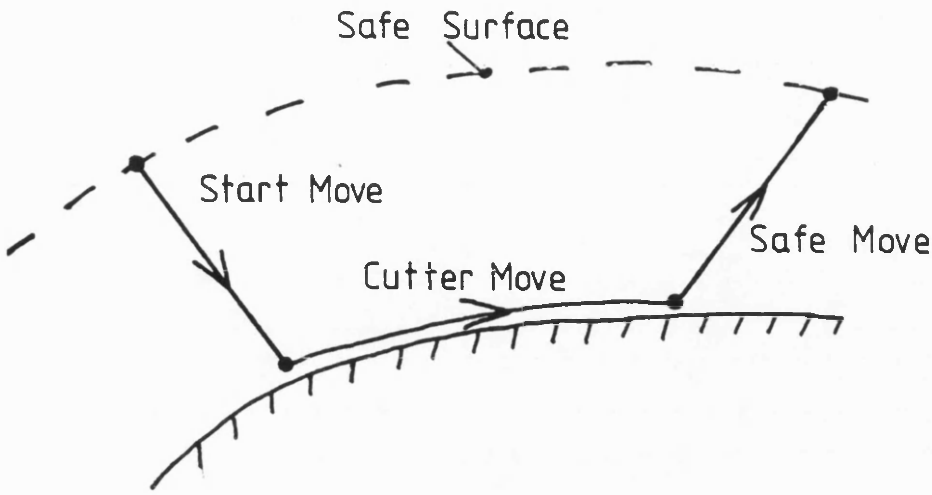


Figure 5.5 Different Machining Moves

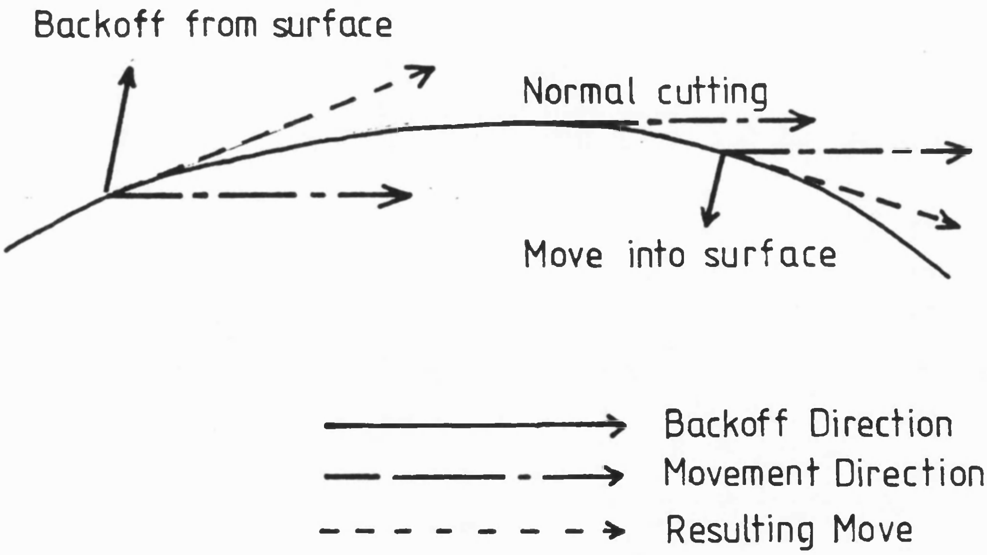


Figure 5.6 Backoff Vector

machining level is achieved (fig 5.6).

A cutter move monitors both the hard and soft case. When the feedback is too high the arm is moved along the backoff vector. When it is too soft it is moved in the opposite direction. The arm is continually moved untii if falls within the desired cutting levels. If the backoff vector is used then the robots coordinates are updated. When backing off an axis may move in a different direction to that of the current move, so the acceleration values are reset and the move ramps back up to maximum speed. The net result of this is that backoff vector and the DDA path combine to form a path around the surface of the component (fig 5.6)

5.3.2 Backoff vector

x

The backoff vector is derived off-line from the computer model. The vector must be simply defined and ideally consist of a single step for one of the axis to give the most accurate positional movement away from the surface.

The initial idea was to select the robot axis closest to the direction normal of the point (2). A point 1mm. off the surface along the directional normal was calculated and the difference in motor steps between the original point obtained. The axis with the largest movement was chosen as the backoff direction. This simple form was not accurate enough for all cases. Instead the following idea was used.

The 3-D surface point coordinates are transformed into the motor coordinate system. For each axis a single step is added or subtracted to the position, and the new motor coordinate converted back into the component system. The vector between the old and the new position is compared to the direction normal and if the angle between them is small then this axis is selected as the backoff. If no accurate solution is found then the direction formed by the combination of two axes are tried and then three axes. The closest case is stored if an exact solution is not found.

The backoff vector is encoded similarly to the output word for the stepper motors. The low byte is used to store which motors are used by setting the coresponding bits to one, and the directions are specified by the high byte. This word is sent down to the bottom processor along with the movement data.

To move down the backoff vector in the opposite direction the bottom processor simply complements the high order byte to reverse all of the directions.

5.3.3 Sampling the feedback

The feedback value is sampled after every step regardless of whether it is a cutter point or a surface point. The sampling is started by setting bit 16 of register B of the DRV11-J high. This rising edge will cause the start of conversion pulse for the ADC. After 12 us., the data can the be read back from the high byte of register A.

The running average is now performed on the data. The last twelve samples are kept in a ring buffer. A pointer shows the next free entry in the ring buffer and the value currently stored there is subtracted from the running total. The new value is stored in the list and the pointer incremented. The current intensity is then added to the total. The total can then be compared to the stored tolerances to obtain the cutting conditions.

5.3.4 Control of the abrasive system

The air motor is controlled by a 12 V. solenoid valve. A relay is switched by a TTL level to activate the valve. The signal is generated from the msb of the low byte of port B of the DRV11J and is active high.

The belt speed is monitored by a magnetic pickup which is interfaced to a frequency to voltage convertor. The output from the convertor is compared to two voltage levels. One for when the motor is running too slowly or stalling and one for when the air motor is free running after the belt has broken. The levels were obtained experimentally. The output from the comparators is combined as a single signal which is active high. This is connected to the msb of the low byte of port A of the DRV11J.

When the signal goes high and the robot is machining, it will automatically back off from the surface and wait for the motor to restart. If the motor does not restart or if the robot is not scurfing, then the belt has broken and the current path is halted and the air motor switched off. An error condition is noted and all movement is suspended until the belt is replaced and the system restarted.

5.4 Overall control

The system is controlled by the following operations. After initial zeroing, the top processor sends down the complete path for a scurfing or an inspection move. It is read in via port C of the DRV11-J, and contains a list of coordinates that define points on the safe surface and the component surface. It has a particular format that was specified by S. Jenkins (2). Three pieces of control data are sent down: the number of safe points; the number of cutter points; and the move velocity expressed as percentage of maximum permissable speed. A list of coordinate data follows. The safe and cutter points are defined as seven element coordinates, in addition the cutter point has two feedback tolerances and a backoff vector.

Successive path data is stored in the format shown in figure 5.7. Whilst the robot is moving it reads the control data and the coordinates for the next path, before reaching the goal position. This ensures smooth continual movement of the robot preventing the abrasive head from excessively machining the surface while waiting to read data.

The data tranfer is achieved by utilising the delay that occurs between successive step pulses (sec 5.1). The data transfer is controlled so that a fixed number of delay counts correspond to the time taken to read and store a piece of information. Before reading in the next piece of data, the amount of time left before the next step is checked. If the delay is not long enough to read and store the data no more data is read until the next step occurs.

During the inspection cycle, the robot must wait while the image is captured and analysed before moving to the next position. The next inspection path is read at this time.

If a path is specified as having no safe moves and no cutter moves then the next path is a zero move. These are sent regularly during a machining cycle to ensure that positional inaccuracy due to

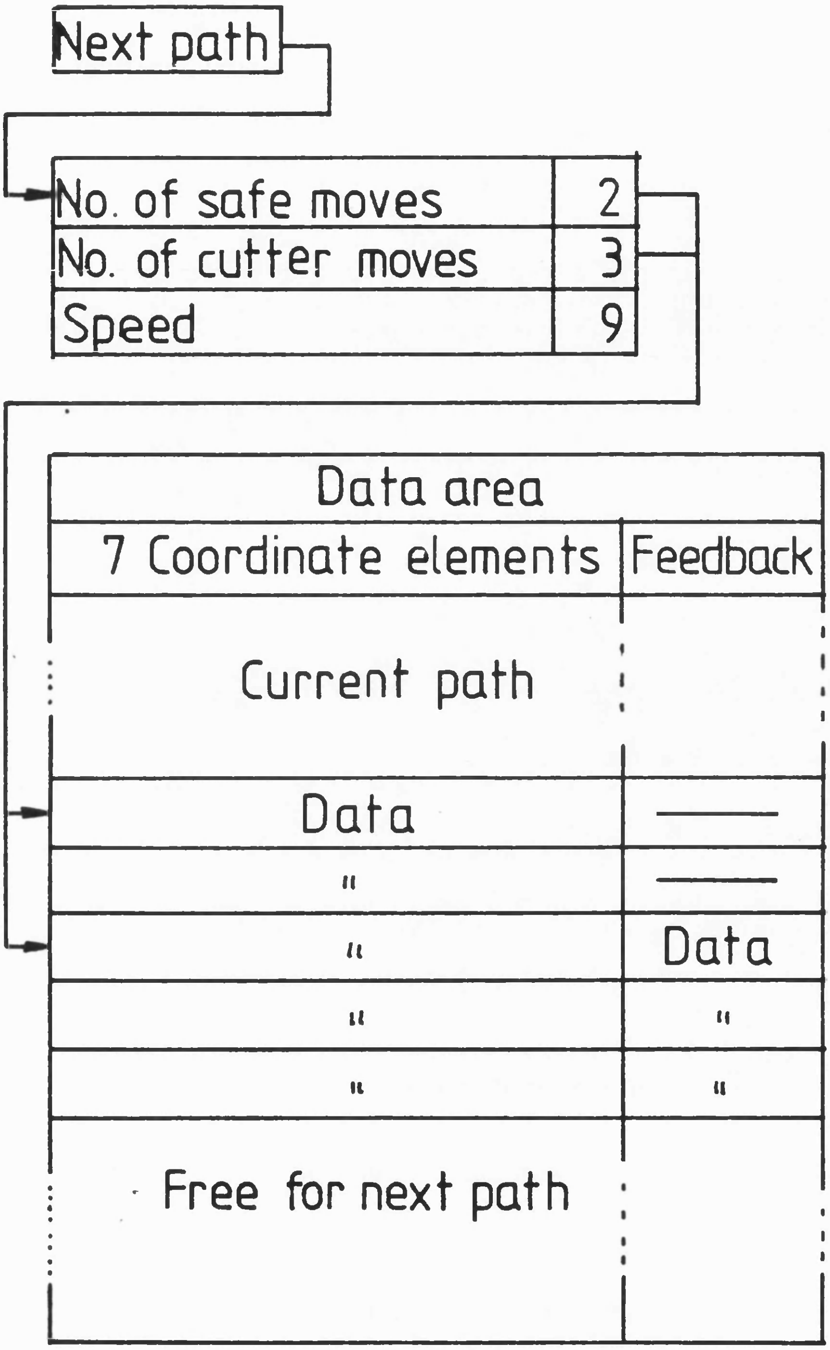


Figure 5.7 Storage of Path Data

lost steps are is not excessive.

When a path is completed the bottom processor will send a reply back to the top. If an error condition occurs during the move a negative value is sent, otherwise it is positive. The robot will continue reading in paths until either the final zeroing move is sent down from the top (signified by a path of -42 elements), or the system is halted by the operator.

The bottom processor scans the console keyboard and if an 'H' is typed the current move is halted. The operator can then either reset the robot by moving it to the zero position, or examine the position and feedback registers, or resume the move.

5.5 Implementation

The system has been successfully implemented in the program BOTTOM and its associated routines (appendix C). Further features have been included that allow keyboard control of individual axes for zeroing and incremental movement. A modular construction of the final program combined with common data areas ensures flexibility and ease of expansion.

All desired features have been included within the routine. Movements are calculated and executed reliably, with no delays caused from I/O to the top processor or the vibration feedback. The program is independent of the robot and the component geometry and modifications can be made to either without altering the program. Movement can be halted from the keyboard at any time and the position registers examined.

The successful completion of this stage of the project concludes the early system design. The next chapter discusses the robot commisioning tests.

6. COMMISSIONING OF THE ROBOT SYSTEM

With the development of the adaptive control system and the movement software, the entire robot system could be commissioned for the first time. The path planning strategy developed by S. Jenkins (2) was tested on a simple geometric shape. The shape chosen was a singularly curved surface, a cylindrical bar, which can be analytically modelled ,and reduces collision avoidance problems.

The scurfing operation was executed upon the component. The robot successfully moved around the cylinder and controlled the scurfing, although the cycle time and surface finish were below specification. To improve the finish, different abrasive head configurations were tried until a more compliant system was obtained. The new configuration was more successful but it was felt that further improvements could be obtained through changing the on-line path planning strategy, by letting it considerthe local surface geometry of the component when choosing the direction of scurfing movement. The chapter describes the commissioning test and the resulting surface finish, and the modifications made to the abrasive system. A new arm configuration is then described along with the new path planning strategy

6.1 Review of S. Jenkins' Path Planning Strategy

The path planning strategy (2) has been previously described in depth in section 3.5. The surface of the component is broken down into patches, the polishing groups, and the group is scurfed by moving around a set of set of points within the group.

The polishing groups are constructed from the triangles that represent the surface of the component. The triangles are grouped together using the requirements of the vision system, i.e the group must be within the field of view and reflect local flatness.

Inside each group points are distributed evenly, and on average are about 2-3 mm. apart. Adjacent points are linked together to form an inter-connected set of paths. A travelling salesman algorithm is used on-line to move the abrasive head to every point within the group. A pair of points are used to define paths to the adjacent groups. In order to cover the entire group a point on the surface may be visited more than once.

All groups are initially polished once. Successive groups are chosen by finding the shortest distance in robot coordinates. To avoid longer moves via the safe surface adjacent groups are considered first.

6.2 Preliminarly results.

An initial commissioning stage was performed upon the robot where all the axis were calibrated and backlash values obtained. Each motor was tested to derive the optimum acceleration and stepping constants. When completed a brass cylindrical test piece was used to test the path planning. It was 80 mm. long and 30mm. in diameter. The component is made from drawn bar and has a higher surface hardness than a cast component due to the cold working process. It consequently requires a higher machining intensity. These factors were not considered too important as the intensity of the grinding can be reliably controlled by the adaptive control system

For the tests two component model data bases were generated:

i) An accurate model that was analytically produced; and
ii) A coarser model constructed using the triangulation package on data obtained from the coordinate measuring machine (CMM).

With both databases the groups were no larger than 15 mm long and are limited in width by the curvature of the component to a single triangle (fig 3.14). The grouping produced between 115 and 120 groups and about 2000 surface points for polishing. Different points on the component were tested to obtain the correct feedback tolerances, and were found to be consistent over the entire object. With a maximum grinding intensity of 255, correct machining conditions were set with a high level of 78 and a low level of 24. A scurfing cycle was then executed using the coarser database.

On a global level the control system executed the scurfing cycle successfully. The abrasive and inspection heads were positioned accurately around the workpiece with no loss of position through motors stalling or backlash. The system correctly calculated paths around the component encountering no collision problems. Each group was accessed correctly from one of its neighbours or via the safe surface. The adaptive control system maintained the grinding intensity without stalling the grinding motor or causing the abrasive head to leave the surface. The speed of the robot was slow, the cycle taking 20 minutes to cover the entire surface, and was considerably longer than desired.

The operation was not so successful when considering the surface finish. The resulting component is shown in figure 6.1.a Obvious errors can be seen where the component has been subjected to gouging. Additionally the surface is highly faceted, and parts of the surface near the split line have not been machined. Generally the cylindrical shape of the component has not been maintained.

In case the CMM generated model was too inaccurate the cycle was repeated using the analytical data. The only effect was to partially reduce the alignment problem at the split line and on the edges of the component. It was decided to use the analytical data for the rest of the commissioning tests so that inaccuracies from the model could be reduced.

From observing the abrasive head during the cycle a number of faults with the scurfing operation were identified which were believed to produce the excessive cycle time and surface finish problems.

i) A major problem existed with the alignment of the abrasive head to the cylinder. The arm was generally seen to oscillate between +/- fifteen degrees to the correct position, and there was severely misaligned at the edges and along the split line.
ii) The cycle was made up of a series of localised short moves and assuming ideal contact, portions of the surface were being machined repeatedly.
iii) The general direction of the scurfing action tended to be along the axis of the cylinder.
iv) There was a reluctance for the robot to move across the

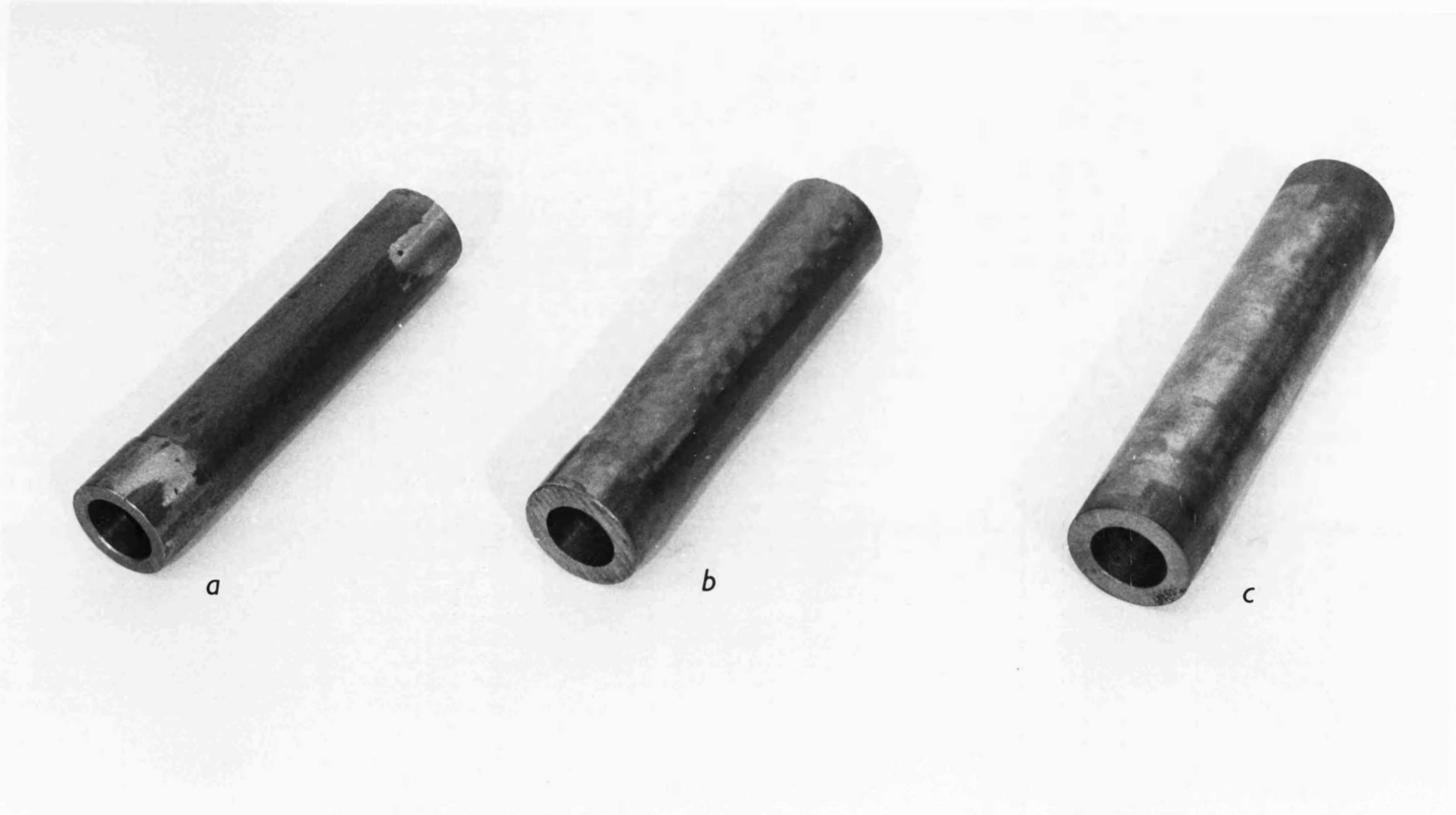


Fig 6.1 Scurfed Testpieces

split line to a neighbouring group.

The gouging was caused by misalignment between the roller and the cylinder and occurs predominantly at the split line and on the edges of the component. When the roller was misaligned there was only limited contact with the component. It was established from the feedback analysis that the intensity of the signal is dependant on the number of particles in contact with the component. If only half of the abrasive belt is machining, the signal will appear low causing the normal force to be increased. Similarly with the edges of the component not all of the belt was used, so the cutting force is too high.

The orientation of the roller was calculated in one degree intervals by measuring the area between the roller and the computer model. The resolution was increased, but an error of five degrees still occurred over most parts of the component, and increasing near the split line and at the edges of the model. The triangles on the edge and on the split line are constrained on one side by the vertices on the boundary of the model, and are more inaccurate when compared with the true shape.

The oscillations of the polishing head had a large effect upon the excessive cycle times, because of the high resolution of the revolute axes. A small angular movement required large revolutions of the stepper motors, because the resolution of the axes were doubled when the harmonic gearboxes were substituted. The direct nature of the drives meant that they could not be driven at the same speed as the stepper motors on the linear axes without stalling. By examining the coordinates of the moves the rotation of the polishing head was found to increase the move in terms of time by a factor of five.

Another factor seen to lengthen the cycle time is the limited compliance of the roller. There is very little contact between the roller and the workpiece, and to compensate a larger number of points were included within each patch. This resulted in many short moves. For each move the robot must remove backlash and accellerate up to full speed and this becomes a significant time factor (about 10%) with the very short moves.

The faceting occurred as the robot moved along the groups because there is little compliance in the roller. When there is perfect alignment between the roller and a cylinderical component there can at best be line contact on a cylinder and point contact on a doubly curved object (fig 6.2). The abrasive head tends to moved along the groups parallel with the axis of the cylinder. It therefore traced lines across the surface creating small facets.

Not all of the component surface was machined during the cycle. This occurred predominantly around the split lines as there was a reluctance for the robot to move across the line and blend into the mirrored half of the component. Additionally the roller did not yield sufficiently (fig 6.1.a), to bridge the gap between adjacent points. The inaccuracies of the triangles around the split line, prevented the creation of groups that bridge the split line, and when moving from group to group, forced the system to select laterally adjacent groups before radial ones. To cover the entire surface with the hard roller the density of surface points would have had to be increased. This was unacceptable because of storage problems, and the time needed to visit every point.

The lack of compliance (the ability to yield) of the small hard roller was a large factor in causing the surface defects. Through increasing it or modifying the abrasive system to increase the area of surface contact, misalignment and bridging problems can be reduced. This would not improve the length of the cycle time with the current path planning strategy and this was considered later.

6.3 Compliance

The 20 mm. diameter roller was selected for the end of the polishing head to facilitate access to a wide variety of components (fig 3.3). The small diameter means a high angular velocity for the roller of the order of 2000 rpm. Coupled with the tangential and normal loads of the grinding an adequate sized bearing only leaves room for a thin 1.5 mm layer of conforming rubber. The development of the feedback established that the normal cutting force is low and a considerably higher load is actually needed to deform the rubber.

The low level of compliance meant that the roller had to lie parallel to the axis of the cylinder to ensure maximum contact, but the inaccuracies in the model near the boundary meant that this

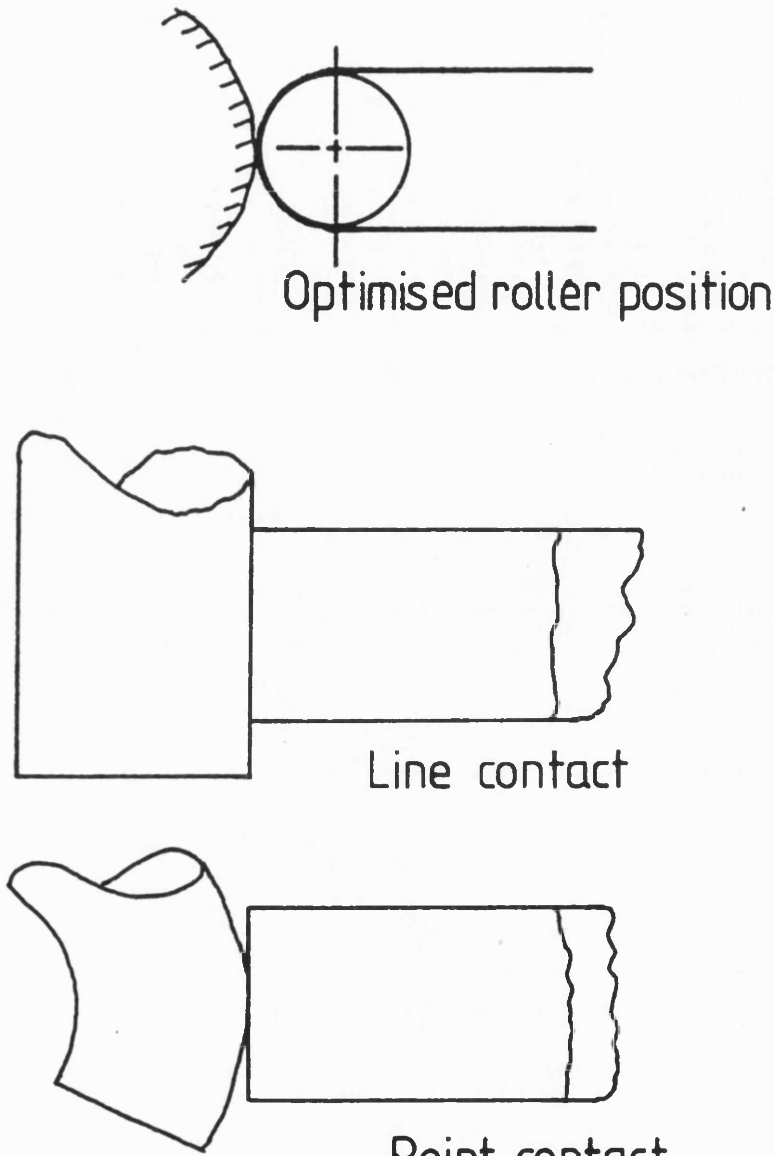


Figure 6.2 Roller Contact to Component Surface

could not be ensured. The calculated orientations are outside angular tolerances and limited contact occurred. More importantly when considering a highly curved object, such as a tap, if there is no compliance there will be only point contact to the surface regardless of the orientation. An improvment in the compliance was investigated through making modifictions to the roller stiffness and altering the arrangement of the abrasive system.

6.3.1 Roller modifications

One of the inputs to the surface point generation was the size of the roller and its position. Therefore modifications could easily be made to the abrasive systems geometry without reconstructing the entire database.

The first approach was to introduce a softer roller. This was achieved by increasing the diameter of the roller to 25 mm. and using an expanded polyurethane foam cylinder as the roller. This roller had a very low stiffness and was partially compressed by the belt tension. The new configuration coud not access all portions of the components shown in figure 2.1, as it had only limited capabilities on the concave surfaces. The cylinder test was repeated, and from the result the following observations were made:

i) The surface finish improved and there was no gouging;
ii) The repetitive localised machining causing facets still occurred; and,
iii) The machining operation appeared to be more severe than that with the hard roller.

Through investigating the feedback signal, the vibration levels were found to be lower than that with a hard roller and the noise caused by movement of the robot within the analysed frequency band increased. The levels were recalibrated but no significant improvement were made to the finish for two reasons:

i) The soft roller could not apply a large normal cutting force without being completely compressed. This caused the belt to be pinched severely between the roller and the component, causing the motor to stall; and,

ii) Removing the unwanted vibrations caused by movement of the robot, removed significant portions of the vibration signal.

It is believed that the soft roller acted like a damper to the system vibrations. This would have caused a drop in the intensity of the machining level and the movement of some of the low unwanted frequencies above the cut off frequency. Although this arrangement has large compliance it was unsuitable as it interfered with the vibration feedback system dynamic characteristics.

Commercially produced contact wheels were available and had been originally considered for the abrasive system, but were abandoned because their size restricted access to the concave surfaces. Due to the unsuccessful nature of the in-house design this approach was reconsidered. A MorrisFlex contact wheel was subsituted for the roller. These wheels come in standard diameters from 50-500 mm. and are manufactured from rubber foam or plastic, with a range of hardness 30,40,70 and 90 (Durometer/Shore Scale). Additionally they included an integral bearing rated to 4000 rpm. They are available in a variety of profiles to suit different machining applications.

From discussions with Morrisflex the general purpose wheel, diameters. A plain face profile, which is recommended for soft grade finishing, and a grooved face were used (fig 6.3). The grooved face has a 4:7 land/groove ratio (the ratio between the width of the groove and the width of the teeth), set on a 30 Helix. It is a general purpose wheel used in oil-free application. The two diameters used were 50 and 100 mm.

The best surface finish were obtained from the large grooved wheel and the worst from the small smooth one. The large wheel has greater compliance because:

i) The grooved face needed a lower force to distort it; and,
ii) The larger diameter produced a higher conformity for the same depth of deformation.

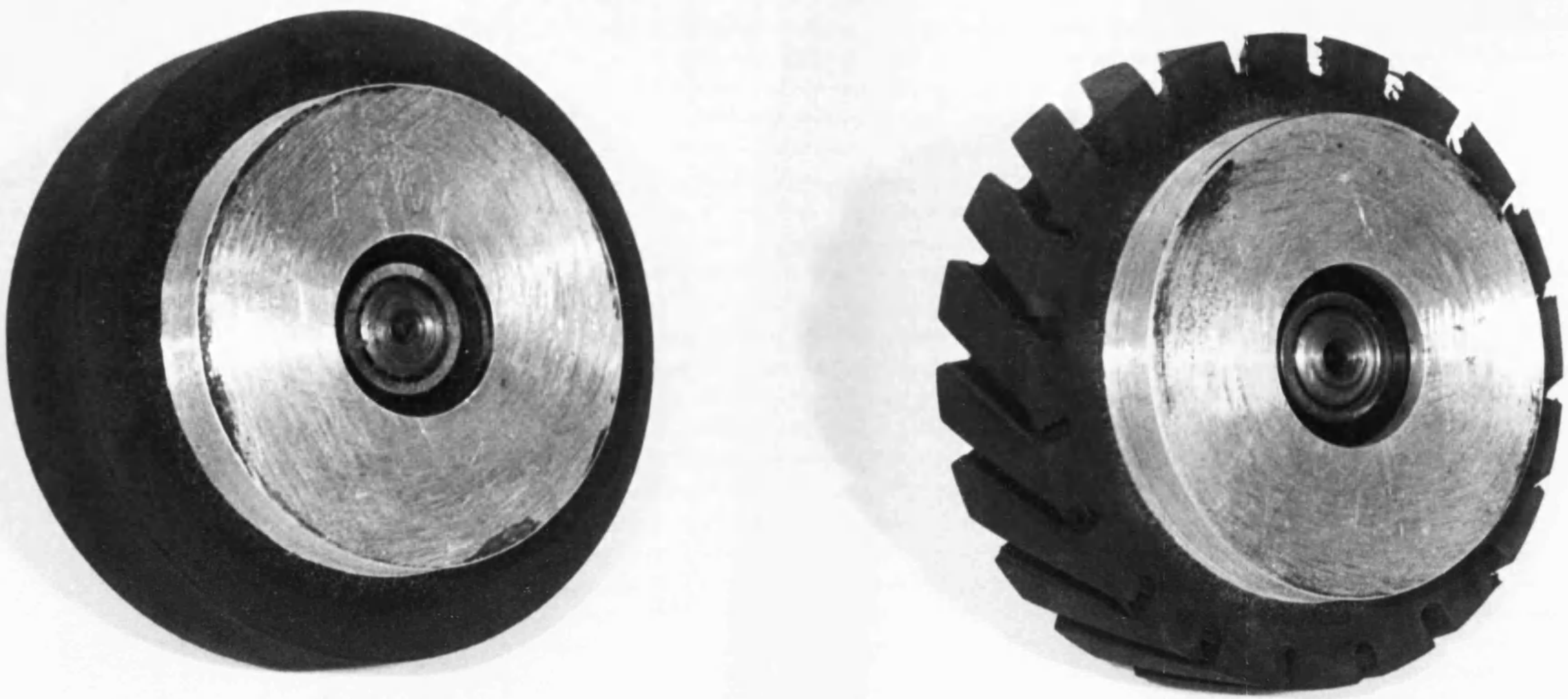


Fig 6.3 Contact Wheels

Increasing the size of the wheel had a large effect upon surface finish. Unfortunately with a complex shape, the large wheel could not access the majority of the surface due to collision problems. A new robot configuration would be needed to accommodate the range of components.

6.3.2 Suspended belt

There was a significant improvement in the surface finish when the radius of the contact roller was increased, and better results were expected to occur with further increases of size. The progression of this is a solution with an infinite radius, i.e. a flat belt.

To achieve this, the belt was tensioned between two rollers. With this arrangement the contact is maximised at all times. The belt lies perpendicular to the direction of the surface normal and maximum surface contact is obtained regardless of the orientation. The system is unable, however, to machine concave geometries. The arrangement shown in figure 6.4 was used to test the idea without redesigning the robot configuration or modifying the database generation. The conversion of the surface points to the robot motor coordinates could easily be made by using a zero radius roller when generating the surface points.

A different type of abrasive belt was needed when machining with a suspended belt. A stretch resistant cloth belt was used over the contact wheel whilst a lighter cloth is needed for a suspended operation. A compliant cloth gives and wraps around a component increasing the machining area and the local compliance. A Norton R222 Metalite J cloth was used in a variety of grit sizes 100,120,180,220, and 240. By examining the metal removal rate a low grit size of 180 or 220 was used in the tests.

The spectrum of the feedback signal showed.

i) An increase in the amplitude of the signal;
ii) Reduced noise; and,
iii) Less vibrations caused by movement of the polishing head.

The greater compliance increased the number of particles in

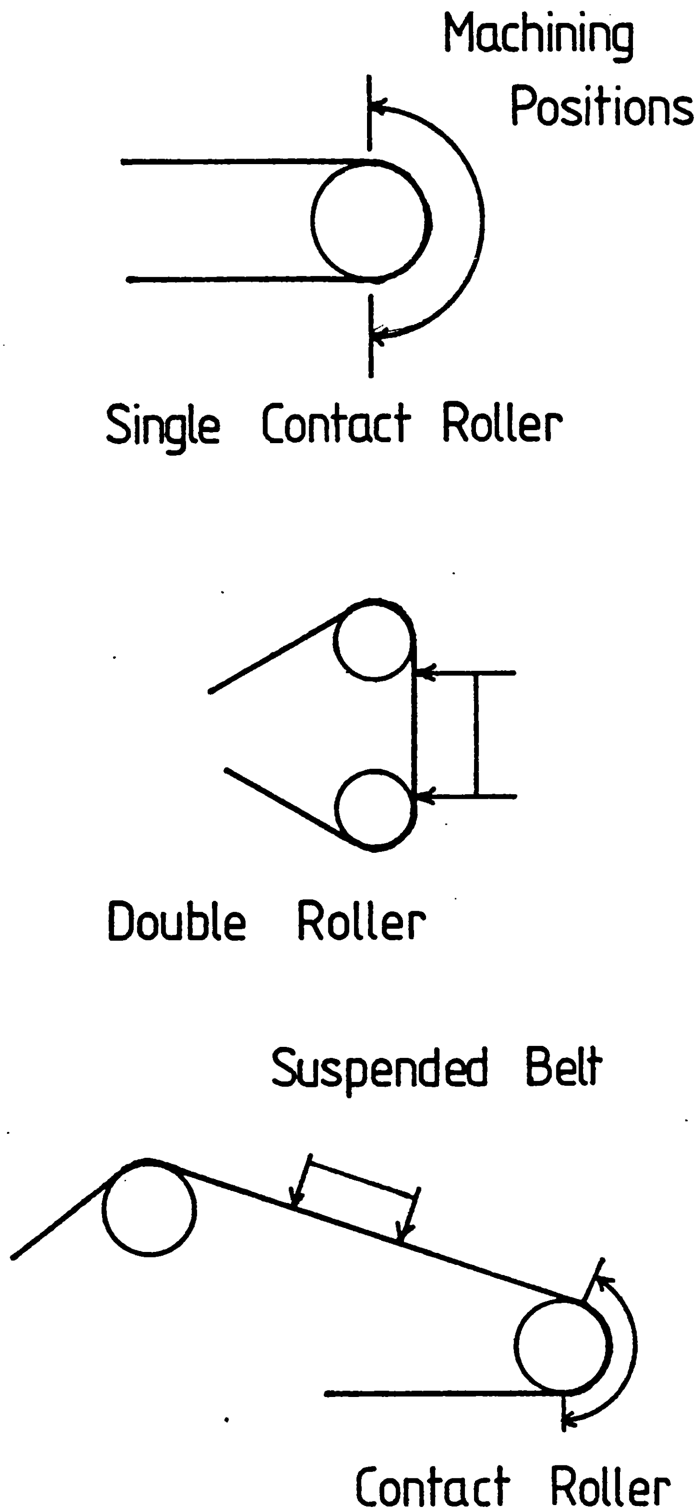


Figure 6.4 Abrasive Workhead Configurtions.

contact with the component and therefore increased the amplitude of the signal. There was no rigid contact between the abrasive head and the component, and so the low frequency signals generated by movements were only transmitted through the supporting framework, and were in fact found to be considerably lower.

The scurfing cycle was run on the robot and the local surface finish greatly improved (fig 6.1.b). The new finish is far superior to previous attempts and it was believed little improvement could be obtained from further alterations of the workhead geometry.

6.3.3 New workhead geometry.

Unfortunately the suspended belt is not suitable for all components particularly ones with concave sections or complicated geometries. However it was more important to prove that an adequate surface finish could be achieved on a doubley curved surface. An acceptable compromise was obtained through limiting the range of the components and combining features from different workhead configurations. An important point to consider is that the majority of concave portions of a typical component such as a tap are on the underside. When these components are commercially machined, the bottom surface which is not in view once the component is fitted, is not finished to such a high standard.

The small grooved Morrisflex contact roller had a reasonable compliance, and was considered to produce an acceptable surface finish for the under side of a component. Therefore the new configuration consists of the small 50 mm. contact wheel and the suspended belt. Commercially there was only a limited supply of 20 mm width abrasive tape, so the belt width was increased to 25 mm (one inch).

The suspended belt could not remain in the same configuration as in the test situation, due to the robot geometry. There was no yaw in the polishing head, so it could only access a limited amount of a double curved surface. Instead the belt was inclined at an angle to the robot axis. The contact wheel was placed on the same position as before on the centre line of the revolute axis (fig 6.4). There are now two positions that can be considered for contact when polishing. The middle of the suspended portion will be used for all convex portions of the surface whilst the contact roller will be used as before for the concave sections.

Although this new configuration was designed to improve the surface finish of the workpiece it had the undesired affect of limiting the number of DoF of the robot to five when using the suspended belt. This meant that the orientation of the belt to the component could not be altered. The author realises that the system had lost some of its flexibility but this ws necessary in order to prove that the desired surface finish could be obtained.

6.4 Limitations of Path Planning Algorithm

Although the increased compliance of the suspended belt had improved the surface finish, there was still heavy faceting causing sharp ridges along the component. By a comparison with the surface model, the facets were seen to reflect the pattern of the groups around the component (fig 6.1.b). The faceting is less marked where there are larger groups and in the direction of the axis of the component.

The manual scurfing operation was investigated further in order to observe the way in which an operator maintained the component geometry. Each movement by the operator was performed with regard to the local curvature. The component was orientated to the belt and then moved so that the belt or contact wheel conforms around the major curve. The motions were large and continuous.

In the case of the robot the moves were short typically 2-3 mm. long and are randomly selected from an off-line generated series of links. The group due to the inspection criteria were lateral in nature, and therefore the links tended to lie along the axis of the cylinder.

To move from group to group the system selected the shortest route in terms of motor steps. When considering the cylinder the majority of movement was performed by the lateral and revolute axes on the work head, axes 2 and 5. The resolution of the lateral axis was considerably coarser than the revolute, a 5mm. lateral movement took 75 steps whilst a similar movement along the surface by the rotary axis required 1000 steps. When selecting the next adjacent group, the lateral group distance were typically 14 mm. apart (230 steps), whilst an adjacent radial group was 5 mm. (1000 steps). Therefore the system would always select the lateral adjacent group first.

With the high compliance of the suspended belt the density of surface points had to be reduced compared to the distribution required for the hard roller, and to mimic the worker the length of the links (the actual moves) increased. Unfortunately if the number of points were reduced then the number of associated paths within a group would also be reduced. This would have been likely to cause repeated machining of the same region, as the robot could only choose from a limited number of paths, and from the previous tests repeated machining has been shown to cause faceting of the component. To produce the desired surface finish the selection of the direction of movement and the density of points within a group had to be reconsidered.

To deduce the effectiveness of the system mimicing the human operator in moving the polishing head around the major curves, a simple test routine was performed upon the cylindrical test piece. The polishing head was simply moved from one group centre to another ignoring all the other surface points. It selected the next adjacent group as the one with the largest relative movement on the revolute axis of the work head, axis five, i.e. forcing the motion around the major curve of the cylinder.

The resulting surface finish (fig 6.1.c) proved better than any of the previous attempts. The majority of the surface, where the arm moved from one radial group centre to another, was smoothly blended with little rippling of the component. However the low density of points meant that the entire surface was not covered, and groups that could only be accessed from the safe surface were not scurfed at all. To cover the complete surface, a higher point density than was was needed, both on the component, and within the surface groups.

The lateral nature of the inspection groups limited the size and direction of links within a group. Reducing the density would leave only four or five points within a group, thus creating limited paths. It was evident therefore, that the group characteristics desired for the polishing operation were not compatible with those of the inspection groups. It was decided to produce two distinct but inter-connected sets of groups for the polishing and inspection tasks.

The system had to raise the standard of surface finish with a robot that has no knowledge of component geometry. To achieve this the following points have therefore been noted about the polishing group, in order to produce continual even machining of a component through using the existing global concepts:

i) Movements must be large (greater than 10 mm) and pass around the major curves;
ii) Generallt the polishing regions needed to be larger;
iii) The density of points within these new polishing groups must be reduced;
iv) The polishing and inspection groups have different characteristics, but one must remain as a sub-set to the other; and,
v) The strategy must be implemented on-line without the robot making use of the component geometry.

The effect upon cycle time has not fully been considered. The reduction in the number of points and larger movement would remove the effect of acceleration and backlash within the moves but would not change the problems of the revolute axes. The cylinder is a sharply curve object, a 5 mm. move around the surface resulted in 20 degres of revolution of axis 5, or 900 steps. Using a larger diameter testpiece or by considering the typical components the movements would result in a smaller angular rotation, for similar length moves, but the time taken is limited by the angular rotation so the effective feedrate would increase. The alignment problem with axis 6 would also be removed when using the suspended belt as the robot can only assume one orientaion and this will be consistent upon a cylinder. The greater compliance and reduced number of moves needed to cover the entire surface facilitate a further decrease in the cycle time.

In the next two chapters, the author discusses the development of new global and local path planning strategy aimed at improving the component surface finish and reducing the cycle times. Chapter 7 describes the creation of the new inspection and polishing groups, whilst chapter 8 discusses the creation of the surface points, the linking, and the on-line selection of the workhead.

7. GROUP CREATION

The commissioning tests identified that larger movements of the abrasive head were needed for polishing, plus using a reduced point density. Additionally the lateral orientation of the small inspection groups and their associated movements, produced facets on the component. Separate polishing groups are needed, that are larger in size and permit motions around the curves of the component. A simple data structure is proposed that makes the inspection groups a subset of the polishing groups, and so maintains compatibility between the two operations. After creating the inspection groups, they will be grouped in turn to create the polishing groups. For clarity the terms inspection 'groups' and polishing 'patches' will now be used.

It is relatively straightforward to create an inspection group as the triangular data structure is regular, but is not necessarily so simple with the patches, as the inspection groups may vary in size and shape. Creation of evenly spaced patches was simplified by making the inspection group boundaries convex. This chapter explains the algorithms that are used to create the new groupings. Although a similar algorithm is used to create both sets of data, the criteria for selecting adjacent triangles or groups differs and hence the processes are discussed separately.

7.1 Inspection Group Specification

The groups are formed by selecting adjacent triangles from the surface model of the component, and adding them together so that the resulting area falls within the specification for inspection. The two limiting constraints on curvature and size are:

i) The curvature must not exceed 12 degrees. This is limited by adding only triangles that have a direction cosine (D.C.) within 10 degrees of the group's D.C
ii) Once the image has been transformed into the viewing plane perpendicular to the DC of the group, the boundary must lie

within a 12 mm. circle of the centre. Previously a rectangular limit was used but the image is rotated depending on the position of the periscope. A 12 mm. rectangle when rotated through 45 degrees will be outside the view of the camera.

The group D.C. is calculated as before by averaging the D.C.'s of all of the member triangles. The centre of the group was previously calculated by averaging the boundary of the object within the world coordinates frame. It is now calculated by averaging in the viewing plane, and then transforming the point back into the world coordinates. Previously for polishing purposes, the centre of the group was constrained as being within the group boundary, this limitation has now been removed.

The process of creating equal sized groups by swapping member triangles must now be replaced by the constraint to create regular convex shapes, otherwise irregular polishing patches will result. Regularity is taken as meaning:

i) A convex boundary; and,
ii) A minimum of triangles connected to the group by only one side.

The process for selecting a seed triangle for a group cannot be random, as it would leave isolated triangles that would not form optimum sized groups and therefore increase the number of inspection groups. Ideally the system should identify triangles that are already bounded by another group or the object boundary. In this way the groups will 'grow' in from the edges of the component.

The permutations needed to be considered to derive an optimum solution will be mathematicaly expensive, so an iterative approach was undertaken. Subsequent passes of the algorithm will re-arrange the data structure, by swapping triangles about to improve the regularity By not allowing the grouping to utilise the full limits of the curvature and size tolerances in the initial stages of group creation, larger changes in model can be performed in the successive stages of the algorithm.

On completion of the algorithm the following group data is required about each group:

i) Centroid and direction cosines and size of the group;
ii) List of all triangles in the group, from this all vertices can be obtained from the data base;
iii) Ordered list of all boundary vertices; and,
iv) List of all adjacent groups.

All of the information within the data base is stored in direct access files (file names and the structure used are shown in appendix D). There is a fixed record length for storing the group centre and D.C. and a blank entry is included that will store the parent polishing patch. The number of triangles, boundary vertices, and adjacent groups will vary between groups, so they are stored in a format referred to as the index/data files (Appendix D).

7.2 Algorithm for creating Inspection Groups

The objective of the algorithm is to break down the surface into a set of regular surface areas using the triangulated surface model. There is no absolute solution and although a mathematical expression for the regularity of the surface groups can be obtained by relating the length of the boundary of the component to its area, the conclusion of the process is made subjectively by analysing a graphical output.

Throughout the explanation of the algorithm, the following two terms will be used to describe triangles, 'two-connected' and 'one-connected'. Two-connected means that a triangle is connected to a group by two of its three sides, whilst one-connected means that it is connected to a group by only one side. See figure 7.1. The two edge triangles marked are one-connected, while all of the others are two-connected. A triangle which is on the boundary of the component will consider the boundary edge as another group

The algorithm works in three stages:

i) An initial pass to create a set of groups. All groups are created by identifying a seed triangle and then considering adding adjacent triangles to it. The algorithm tries to

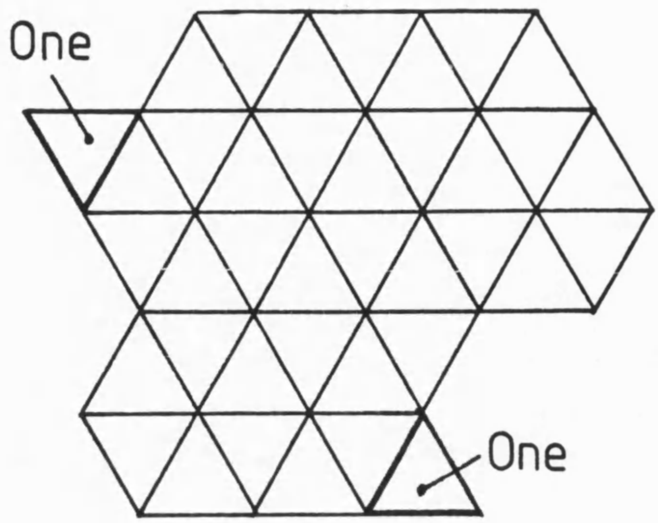


Figure 7.1 One—Connected Triangles

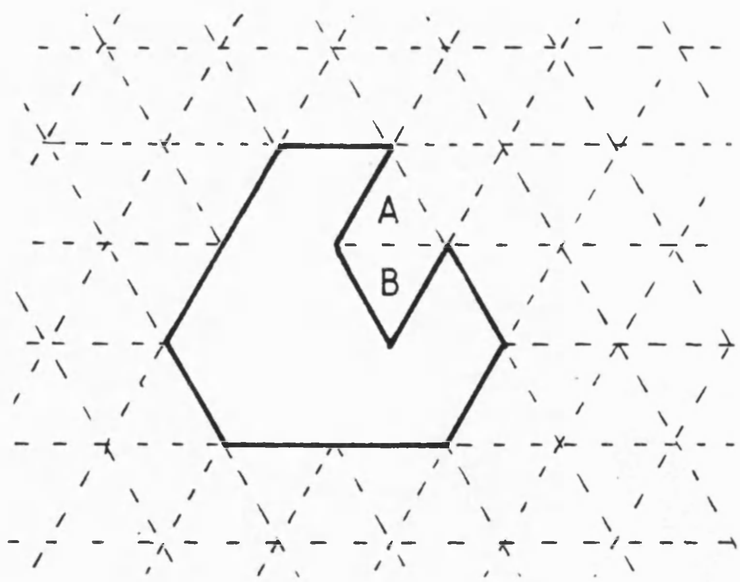


Figure 7.2 Maintaining Group Integrity

optimise the groups and ensures that the number of single triangle groups in the structure is minimal;

ii) The next pass identifies all single triangle groups and it then attempts to include these triangles within a neighbouring group; and finally,

iii) Every triangle is examined to see if it will 'fit' better into one of the neighbouring groups.

Stages two and three are repeated until the final structure is obtained and the data base is stored.

7.2.1 Creating the groups.

An initial seed triangle is found on the boundary of the component. The properties of the triangle, its boundary, centroid and D.C. are assigned to the new group and all adjacent triangles are then stored on a list.

The algorithm now enters the main group creation loop. The adjacent triangles are considered having been ordered in the following way to aid in the forming of regular groups:

i) Distance from the group centroid, nearest first
ii) Connectivity to the group, two connected first.

The effect of sorting is that the nearest two-connected triangle will be selected first and if it is within tolerance then the next two-connected triangle will be considered. When considering a triangle from the list it is first tested for connectivity of the newly created group boundary. It is possible to select triangles that would enclose another group. If triangle A in figure 7.2 is joined to the group before triangle B then this would leave B enclosed and this is prevented by this test. When connectivity has been established, the new group is tested for curvature and size. If the group does not pass both tests then the triangle number is noted and the next triangle in the adjacent list is considered until either one of the triangles pass, or all of the then fail.

When a triangle passes the tests, then the group information is updated. A simple algorithm is used to modify the group boundary whilst maintaining its continuity. Any adjacent triangles of the new triangle that have not already been included in a group are now added to the adjacent list. The new list is then ordered and the process repeated until there are no suitable triangles in the adjacent list.

The group is now completed and all of the data stored. A new group is formed by finding a seed triangle that has not previously been included in a group, considering in order the following conditions (fig 7.3):

i) A triangle that is connected to two groups;
ii) The nearest triangle to the previous group centroid ,that was rejected from the group; and,
iii) A triangle on a boundary connected to a group;
iv) The nearest triangle to the previous group c.g.

If no new seed triangle is found then all of the triangles have been grouped.

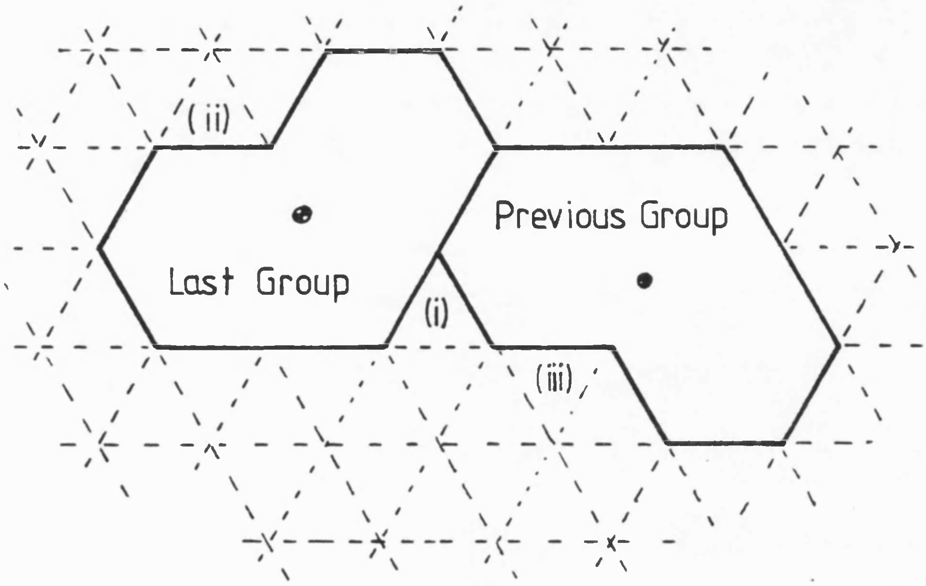
7.2.2 Removing single triangle groups

The data base is searched and single triangle groups are easily identified (fg 7.4.a). The group will be modified if it is either:

i) Two-connected to a neighbouring group; or,
ii) Has one-connected adjacent triangles.

If the triangle is two-connected, then the program tries to include this single triangle within the surrounding group (fig 7.4.b). This may be possible as the initial grouping does not utilise the full tolerances of the inspection size and curvature constraints. If the triangle can be included, the single group is deleted from the database and the new larger group updated.

If the single triangle does not fit into the group, the algorithm swaps the triangle with one-connected triangles in the surrounding group (fig 7.4.c). If the new group is within tolerance the two-connected group is updated and the removed one-connected triangle becomes a single group. This single group may well be



i) Triangle connected to two group

ii) Nearest triangle rejected from last

iii) Triangle on group boundary

Figure 7.3 Identification of Seed Triangle

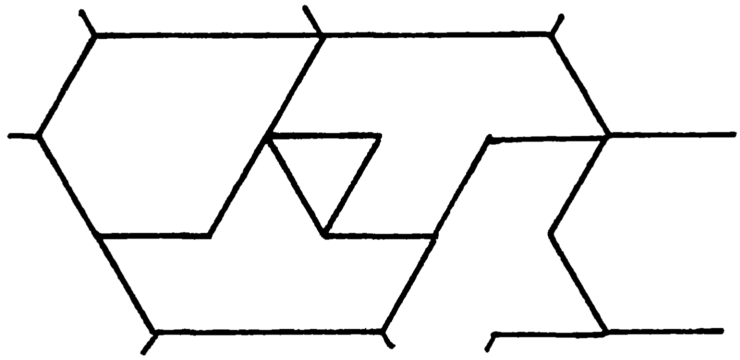


Figure 7.4.a Single Group Triangle

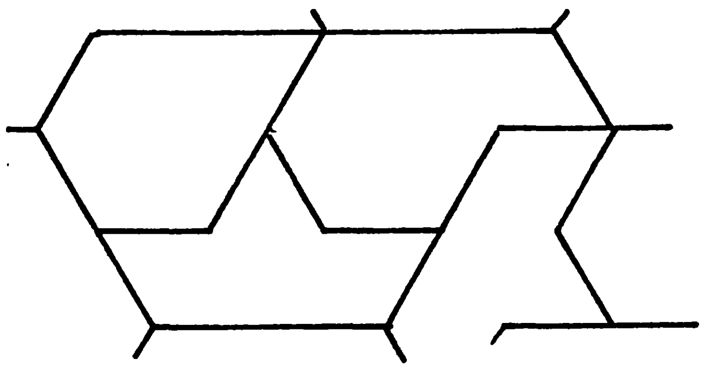


Figure 7.4.b Inclusion of Single Group Within Another Group

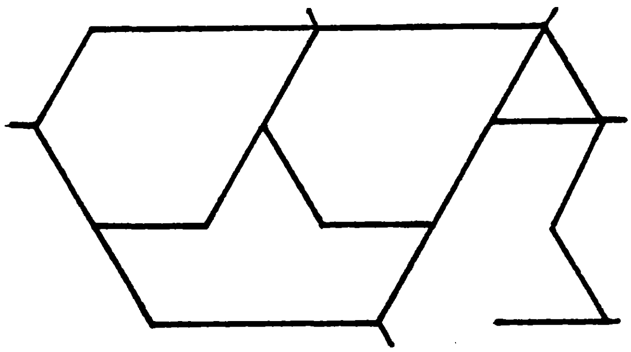


Figure 7.4.c Rippling Single Group Through Another Group

Figure 7.4 Removal of Single Triangle Groups I.

eliminated in later interations of the algorithm.

Finally, if a single group is not a two-connected group or if it cannot be included into another group, the algorithm increases its size by removing any adjacent one-connected triangles from the adjacent groups, and joining then to the single group (fig 7.5). An important point to note is that when the algorithm alters a group, the change in the boundary may change the adjacent groups.

7.2.3 Optimising of groups

During the initial creation of the groups and when modifying single groups, the algorithm may create a group which has an adjacent two-connected triangle (fig 7.6). The data base is searched, and on finding such a triangle, the algorithm will try to fit it within the connected group. If the new group is out of sepcification, it removes one-connected triangles and tries again. If a fit is found then the group is updated. Any removed triangles becomes a new single group, to be modified on later iterations.

If no two-connected triangles are found, the number of triangles in each group is considered. When there are less than five any adjacent one-connected triangles are added. The iteration continues until all adjacent triangles have been considered. In this way two small adjacent groups can combined.

The last two stages can then be repeated modifying the new single triangles and the changes to the data base, until an adequate solution is found.

7.2.4 Implementation and Results

The algorithm was written in Fortran 77 using the VAX 11/730 as the package 'CREGRP'. It utilises previously developed routines that can extract triangle and vertex data from the database, and the position and direction cosines of any vertices within the group.

The algorithm was tested upon a doubly curved surface, an analytically shaped barrel. Subsequent tests included two measured components viz a tap and a header tap.

The program can display the grouped data base as a plan view at each stage of the grouping. A typical output after the first stage

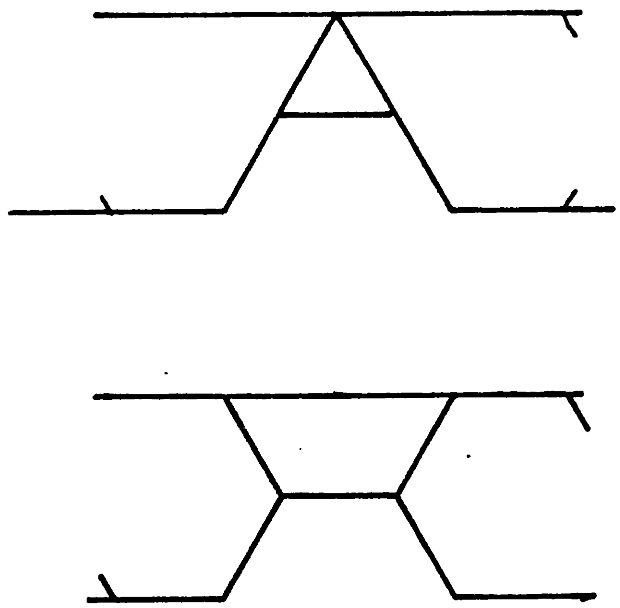


Figure 7.5 Removal of Single Triangle Group II

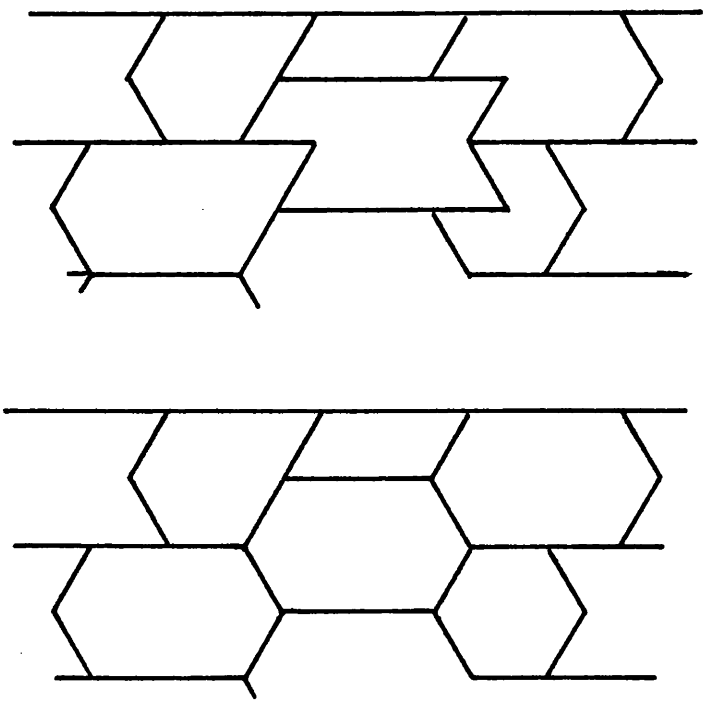


Figure 7.6 Removal of Concave Boundaries.

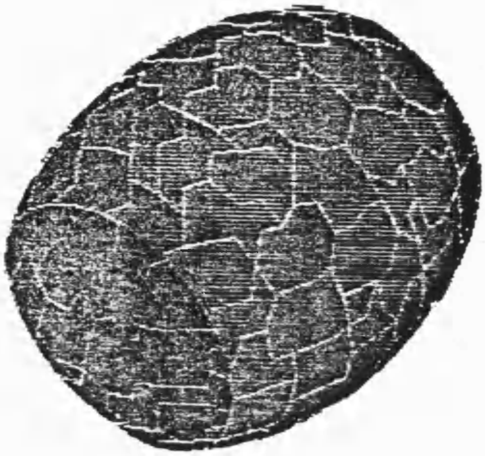


Figure 7.7 Grouped Component

is shown in figure 7.7. There are a number of single groups within the data base and a lot of two-connected triangles. Successive stages remove most of the single groups, (therby reducing the number of groups within the data base) and all of the two-connected triangles.

Normally the second and third stages of the algorithm are repeated three or four times, after which they have little effect upon the data base. The program copes with all shapes equally well and produces a reduced number of groups when compared with the original algorithm.

7.3 Polishing Patch Specification

The polishing patches are formed by joining together neighbouring inspection groups. The major considerations for forming the patches will be a trade off in producing enough patches, so when defects are identified and machined, excessive amounts of the surface will not be covered, and the desire to have long movements around the major curves. Another important consideration is collision avoidance. On the system only simple static detection can be employed with no regard to the dynamic detection. To reduce problems caused by creating groups that will inherently interfer with the work head, the curvature of the patches must be limited. There are no defined tolerances, but patches are expected to be typically between 20 and 30 mm. square and wrapped around the major curves of the object.

The D.C. of the patch is to be calculated as the average of all of the triangle D.C.'s. The centre of the patch must be within the boundary of the object, as this is where the abrasive head enters the patch from the safe surface. The centroid cannot be calculated from an average of the triangles, as on a highly curved object this will be well below the surface (fig 7.8). Instead the centroid is calculated by finding the centre of the patch in the plane of the patch (perpendicular to the D.C.), and then selecting the nearest vertex to this point. If the point is on a boundary then the centre of the nearest triangle is selected.

The final polishing patch must be regular so that the surface

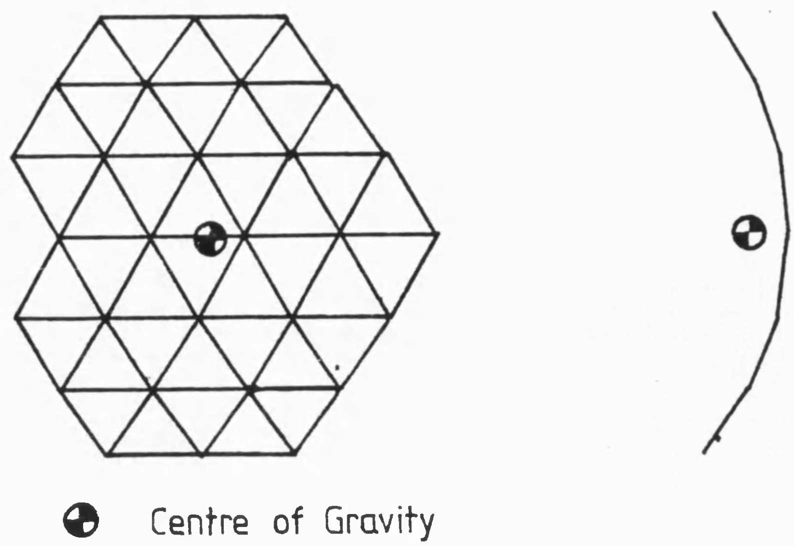


Figure 7.8 Centroid of Patch

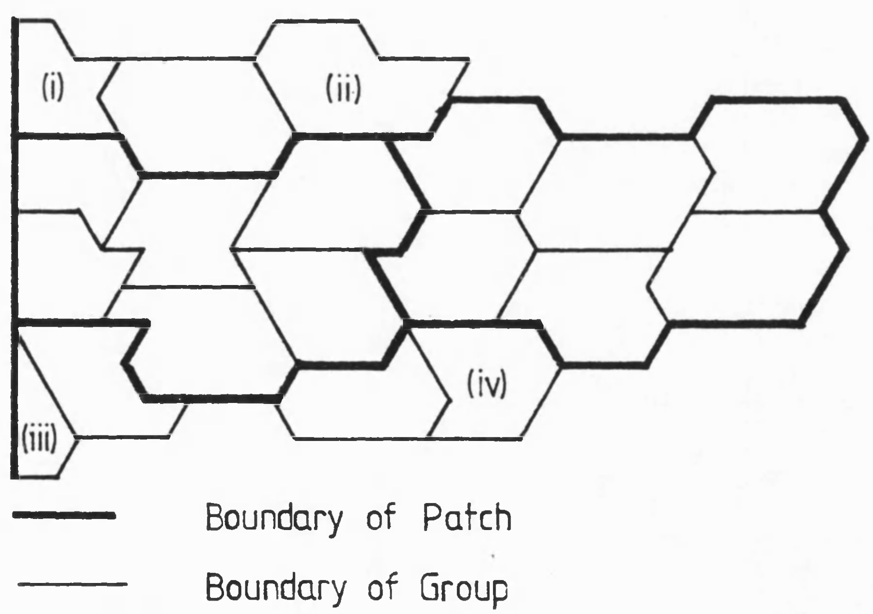


Figure 7.9 Selection of Seed Group

is evenly covered in patches. Single inspection groups should not be left after grouping to form very small polishing patches, as this can result in faceting.

During the initial commisioning, a reluctance was noted for the system to create inspection groups on, or to move over, the split line of the component. This must not cccur with the new system.

On completion of the grouping the following information is needed about each polishing patch:

i) Centroid and direction cosines;
ii) List of all inspection groups in the patch, from this all triangles and vertices can be obtained;
iii) Ordered list of boundary vertices; and,
iv) List of all adjacent patches.

The same format should be used to store both polishing and inspection data, with additional inspection information relating polishing patch membership.

7.4 Polishing Patch Algorithm

A similar approach to the first stage of inspection grouping is used for the polishing grouping. The algorithm performs the grouping in one pass relying upon a graphical output to display the resulting patches. The size and curvature constants are to be input from the keyboard.

There are three stages in creating a patch:

i) Identification of a seed group;
ii) Adding adjacent groups; and,
iii) Ensuring that no isolated groups are left.

After identifying the seed, the second stage is repeated until all adjacent inspection groups to the new polishing patch have been considered. The surrounding groups are then examined to ensure that no group is rejected that would be better suited to membership of the current patch, or a group is not left isolated. The patch is stored and a new seed is found to start a new patch, until all of the inspection groups are committed.

7.4.1 Seed inspection patch

A seed group is identified by searching the database for an inspection group that has not already been included in a polishing patch. It must satisfy one of the following conditions (fig 7.9):

i) An inspection group on the boundary that is connected to a polishing patch;
ii) A group that is connected to two or more polishing patches;
iii) A group on the boundary of the object;
iv) A group that is one-connected to a polishing patch; and,
v) The first ungrouped group in the data base.

Searching in this order ensures that the grouping grows from the edges. If the selection of the seed is random, or if it ignores the edges of the component and previously defined polishing patch boundaries, then a lot of small isolated patches would result. The last case will never be selected as one of the previous conditions will always be satisfied first, and is only included for error condition trapping.

On start up, the object will fail the first two conditions as no polishing patches have been created yet. It will therefore find an object on the boundary, (the component must have at least one boundary as it is attached to the chuck). This will always be inspection group number one as the inspection grouping starts by finding a group on the boundary.

The new polishing patch is updated with the inspection group c.g and D.C., and a list of all unattatched adjacent groups is found.

7.4.2 Adding adjacent groups

The grouping proceeds by the algorithm selecting a group from the adjacent list. To control the grouping the adjacent groups are ordered so that the most 'sensible' is considered first. Two criteria are used:

i) Distance between the group centroid and the patch centroid (nearest first); and,
ii) Connectivity of the group to the patch (greatest first).

The distance obtained from the coordinates of the centres, and the measure for connectivity is found by considering the the ratio of the length of the common boundary, to the length of the inspection group boundary. The groups are first sorted by length and then sorted by connectivity ratio. Thus the groups with the highest connectivity will be selected first, and with groups with the same connectivity ratio the nearest group will be selected.

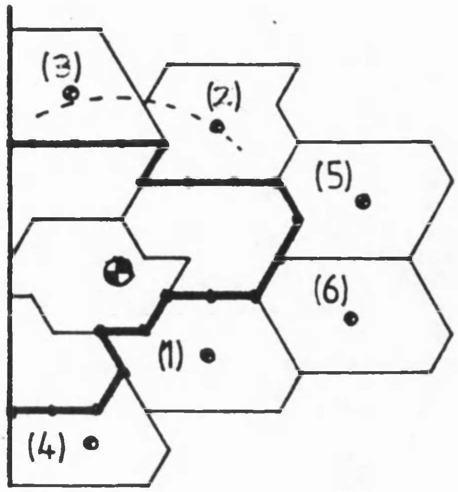
After ordering the groups, each adjacent group is considered in turn for adding to the patch, with the new centroid and D.C. calculated and tested against the tolerances. When a patch falls within tolerance the database information is updated and the ordered boundary is found (fig 7.10). Unattatched groups connected to the joined group are put in the adjacent list and it is re-ordered. The grouping continues until no adjacent groups can be added.

7.4.3 Removing isolated groups

During the initial grouping stage isolated groups may be created, as well as groups whose connectivity are best suited to the patch. These failed to be included within the patch because of the size and curvature tolerances. To prevent this all unattactched adjacent groups are considered for these two conditions. If a single group has been created (Group 1 in figure 7.11),the group is included with the patch regardless of the size and curvature constraints.

The second test is performed upon groups that are only joined to one other free inspection group (Group 2 fig 7.11). The connectivity of the group is considered against the patch and against its adjcent group. If the common boundary to the patch is longer then the group is then the group is included, otherwise it is ignored and will problably be selected as a seed for a new patch.

If the patch is modified then the pass has to be repeated in



Adjacent groups would be ordered in this order on the basis of distance and connectivity.

Figure 7.10 Ordering Adjacent Inspection Groups

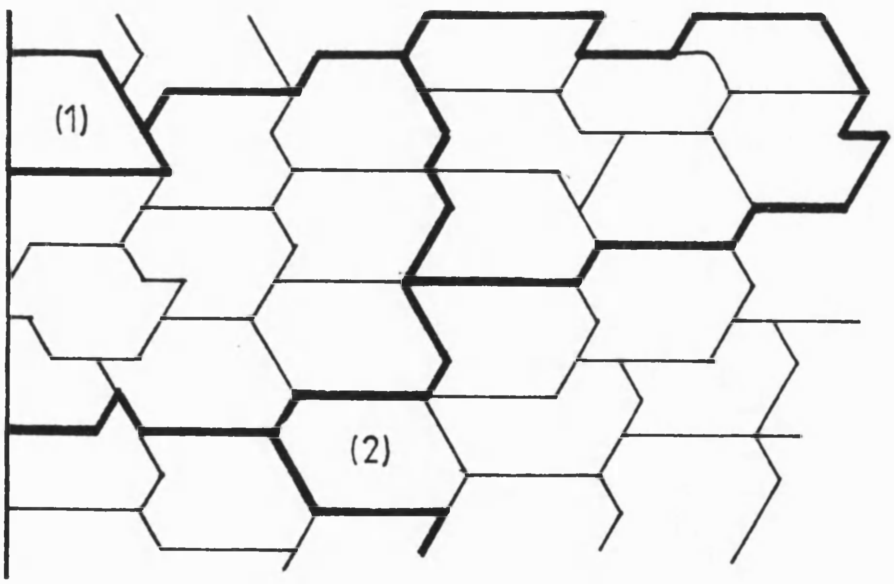


Figure 7.11 Inclusion of Single Groups

case adding a group creates a new isolated group or alters the connectivity.

After all groups have been considered and no group added the new polishing patch is stored and all the inspection groups updated.

7.4.4 Implementation and results

A Fortran 77 program called 'POLPAT' was created upon the VAX 11/730. The grouping was performed upon the analytical and commercial components. The program gives a graphical display and lists the criteria for failing or passing for each considered adjacent group. Alternatively it will perform the operation automatically outputting the results after one minute.

Provided the process occurs from the boundaries of the component and from previously defined polishing patches, a regular structure results. The optimum selection of seed group was found by experimenting with the order of the criteria. Using groups on the edge of the component was found to be the most important, otherwise small irregular patches occurred on the boundary and within the component, increasing the number of polishing patches.

The grouping was not affected by the component split line and no further action was thought necessary in this area.

The parameters for grouping were generally selected as being patches of 20 mm. radius and between 90 and 120 degrees of curvature. No particular values could be assigned to each component and were selected experimentally. Some typical outputs are shown in figure 7.12

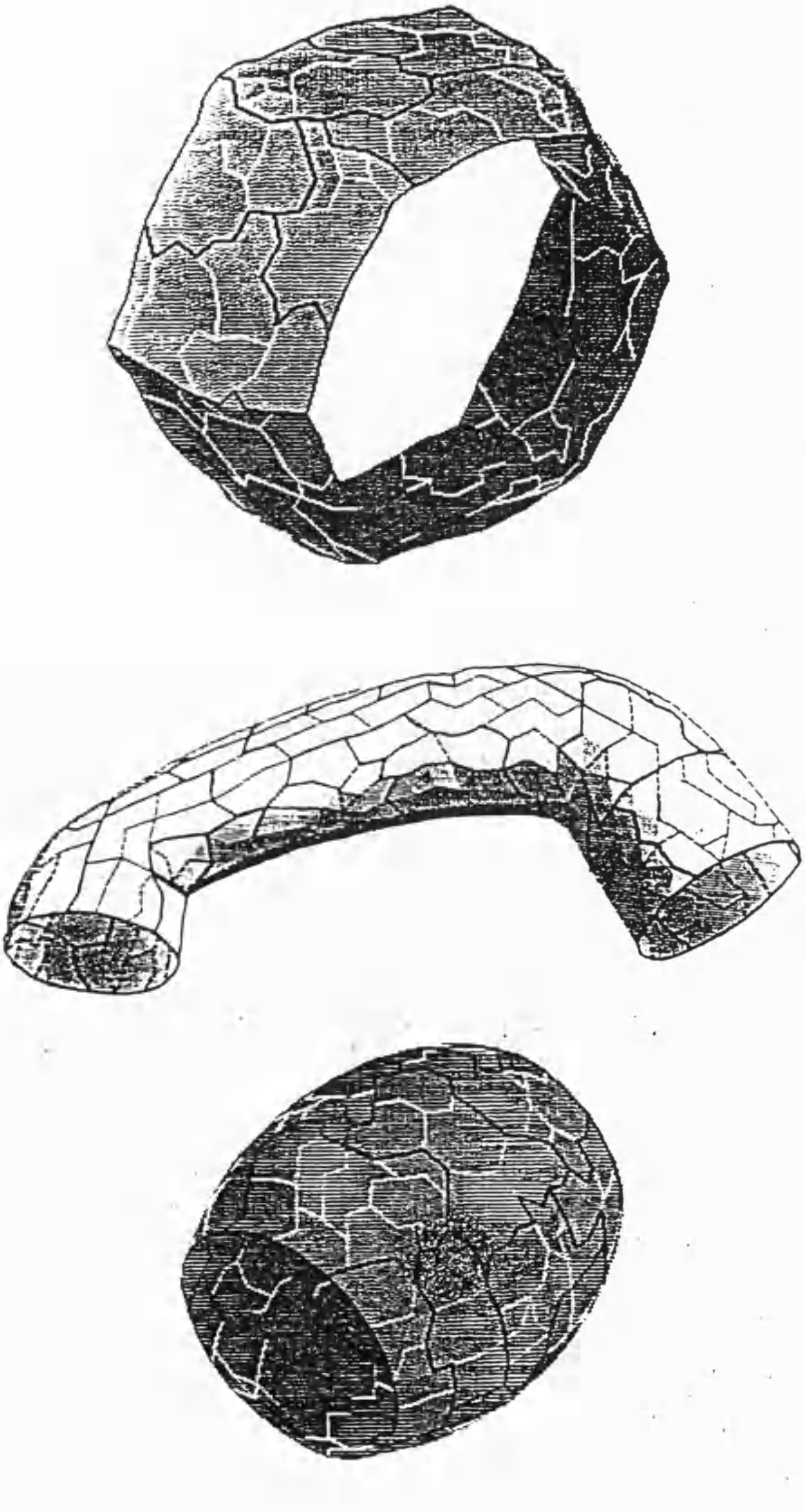


Figure 7.12   Patched Component

8. SURFACE POINT AND ROUTE GENERATION

Now that the new larger surface patches have been created, a method is needed for moving around within a patch, and to other patches in order to machine the surface regularly. To prevent computationally expensive planning algorithms, and to reduce the amount of pre-stored data, an approach was used that creates a discrete set of pre-planned paths for each group. This was performed by distributing a number of points within a patch and creating a set of links to join them together. The same approach is to be used for the new surface patches.

The initial commissioning test identified that large movements were needed within a polishing patch, in a direction that consider the component geometry. Specifically, the movements should be around the major curves of the component, in order to reduce faceting whilst machining. This was achieved by using larger polishing patches with a reduced point density, and links that reflect local component geometry. The points on the component surface (surface points), are selected for either the contact roller or the suspended belt configuration depending on whether the polishing patch is convex or concave. This chapter initially begins with a description of the project approach to collision detection and avoidance, and then proceeds by describing the creation of the surface points and links, and the selection and calculation of the abrasive head position. Finally it describes the on-line implementation.

8.1 Collision Avoidance and Detection

The problem of collision detection and avoidance has not yet been discussed in detail. Both are complex processes which are major limitations in the development of off-line programming techniques involving complicated shapes. In this case two types of collision were originally identified:

i) Firstly, local inteference in the region of the abrasive head which caused an access problem. This was detected through employing a simple interference test developed by S. Jenkins (2) and was discussed in section 3.4.

ii) Secondly, interference between remote parts of the component and robot which cause global collisions. This is a more severe problem, which requires all parts of the component to be tested against the structural members of the robot within the working volume. Whilst simple boxing test may provide a first approximation, reliable results require detailed geometric calculation, which are not readily conducted in real time.

Consequently the global problem was considered in two parts viz, free movement and machining. Free movement describes the movement of the abrasive had about the working volume, but not in contact with the component surface. The strategy used was to define a "safe surface" about which the abrasive head could move in real time without risk of collision. In its simplest form, this would be a cylindrical surface providing an envelope around the component. Provision was then made in the database, to define collision free path from the safe surface to each patch upon the component surface. For a convex shape this would normally be the component surface normal vector projected onto the safe surface. No attempt was made to derive collision free paths for more complex shapes with re-entrant features.

The problem of global collision during machining was not considered at all during the project due to the lack of time and resources. This placed a immediate limitation on the robots ability to cover the surface of a complex shape, but was considered justifiable in the interests of achieving a commissioned system. The full effect of the limited collision detection and avoidance are discussed in chapter 9.

8.2 Creation of surface points

The robot scurfs the component by moving the abrasive head between points calculated from the surface model. These were previously distributed within the inspection group at every vertex, the centre of each triangle, and the centre of the group (fig 8.1). A pair of points were used to link the group to its neighbours. The two points, the bridging points, sat astride the midpoint of the common boundary, one in each group

This distribution typically resulted in a point density of one point per 4 mm . This density was required because of the low compliance of the small contact roller. With the compliant suspended belt the high density produced small movements and caused repeated machining of localised areas, creating a faceted surface. A lower density is required within the larger polishing patches to minimize these problems.

To ensure correct machining of the surface and integration with the existing linking and on-line control, the new surface point strategy has a number of objectives:

i) Calculation of the position and surface normal for each point;
ii) Regular distribution that covers the entire patch;
iii) A lower density of points, typically one per 25 mm ;
iv) An entry/exit point to the safe surface; and,
v) Bridging points to adjacent patches.

The component surface is already represented by the triangulated surface model. A regular distribution of points could be achieved by considering the vertices, but the point density is unfortunately too high for correct machining. A lower one was obtained by thinning the number of vertices using the triangulated structure. Care must be taken in thinning so that points are distributed evenly around the edges of the patch.

The centre of the group was used for moves to and from the safe surface as it still lies within the boundary of the polishing patch. A different approach was needed for the bridging points. Previously the pair of points spanned the common boundary typically 2 mm. apart. With lateral adjacent patches this caused short lateral moves compounding the faceting of the surface. Ideally with the patches, the moves should be longer and follow the major curves.

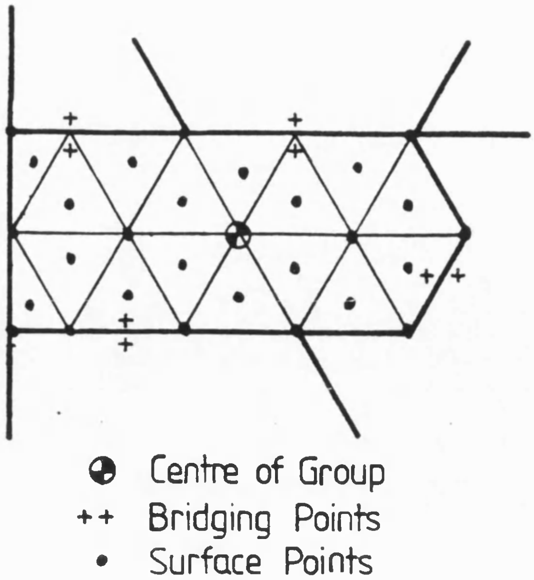


Figure 8.1 Surface Points Within an Polishing Group

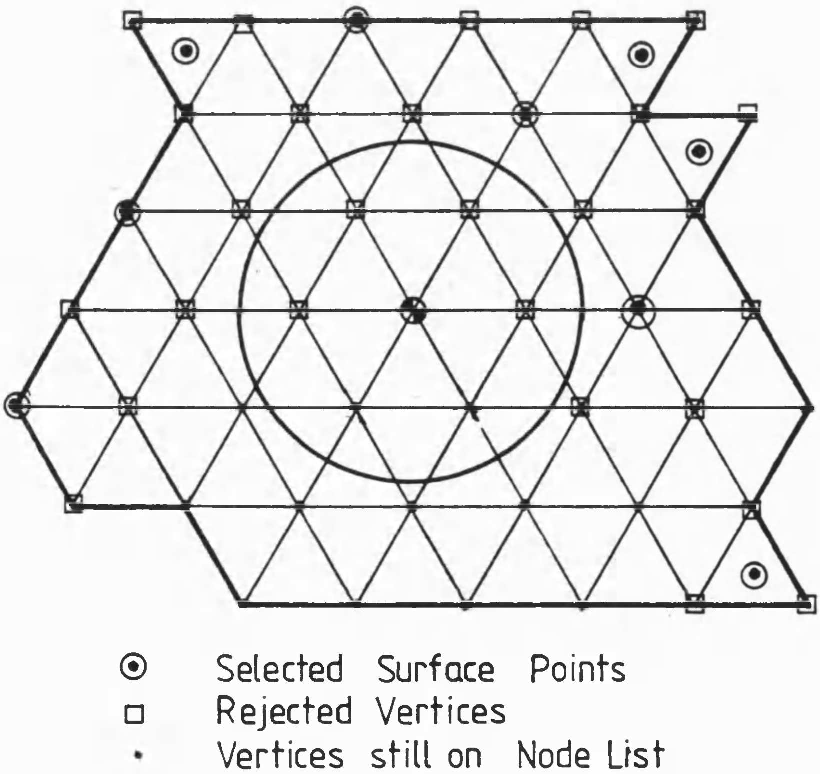


Figure 8.2 Selection of Surface Points Within a Polishing Patch

8.2.1 Algorithm

The algorithm utilises the triangulated surface model data structure. using the vertices within the patch. Each patch is considered in turn, and initially a list is created linking every vertex to its adjacent vertices. This list is usually referred to as the node list.

Due to the sequential approach taken by the algorithm, in considering each patch, a neighbouring patch may have been processed first. The neighbour will already have selected a bridging point into the current patch and this may lie upon the boundary. If this occurs then the vertex is include as one of the surface points, and it and all adjacent vertices are removed from the node list.

To maintain the geometry of the patch, ensuring regular distribution at the edges, any one-connected triangles are tested. From the previous definition one-connected triangles can only occur on the patch boundary. So if:

i) They do not have a vertex which is a bridging point; and,
ii) It is not within 10 mm. of the centre of the group; then,

The centre of the triangle is made a surface point. All vertices of the triangles are then removed from the node list. The remaining vertices within the node list are considered in turn. If a vertex (fig 8.2):

i) Has all its adjacent vertices in the node list; and
ii) Is not within 7 mm. of the centre of the patch; then ,

The surface normal at the vertex is obtained from averaging the connected triangles normals, and the vertex is then stored as a surface point. All vertices connected to the point are removed from the node list. If it fails one of the tests, then it is not considered again and is itself removed from the node list.

When all vertices in the node list have been tested the resulting spread of points is examined identifying if any 'isolated triangles' have been created. An isolated triangle being defined as a triangle that does has not had a vertex selected as a surface point (fig 8.3) Each triangle in the patch is considered in turn and if one is found then it is:

i) Not within 7 mm of the centre of the patch; and,
ii) Not adjacent to a previously selected isolated or one-connected triangle; then,

The centre of the triangle and its surface normal are stored as a surface point. Finally the patch centre is stored as the last surface point.

The bridging points to adjacent groups are now selected. If an adjacent patch has a lower patch number, then a bridging point in the adjacent patch has already been created. If this point is on the common boundary it has already been stored, otherwise the point is within the neighbouring patch. A list of suitable points is created. The list contains all surface points that are connected to the common boundary. If the common boundary contains more than 4 vertices then vertices connected solely to the end of the boundary are ignored. Similarly triangle centres that have been used for surface points are included if they have either:

i) Two vertices on the common boundary; or,
ii) One vertex on the common boundary and no other vertices on the patch boundary.

The list of points are tested to find the one with the largest angle between it and the adjacent patch bridging point, and this is selected as the patch bridging point. It is possible that the same bridging point can be used for more than one adjacent patch.

If the adjacent patch has a higher patch number then there is no adjacent bridging point. A surface point is found by considering the patch surface points in the following order:

i) A point on the common boundary that is nearest to the middle of the boundary. The end points are only considered if the boundary has 4 vertices or less;
ii) A vertex connected to the midpoint of the boundary; and
iii) A triangle centre that has the midpoint as one of its

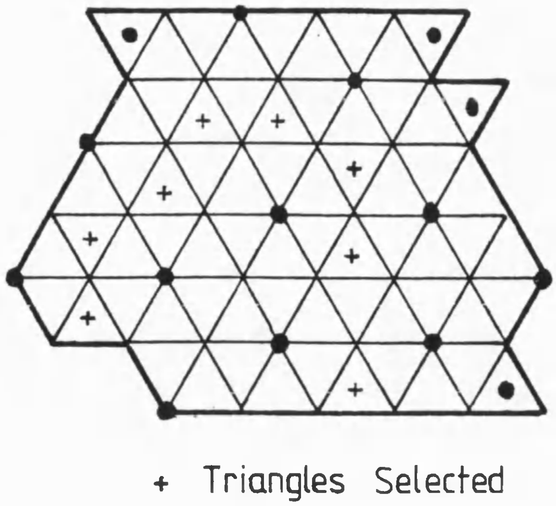


Figure 8.3 Removal of Isolated Triangles

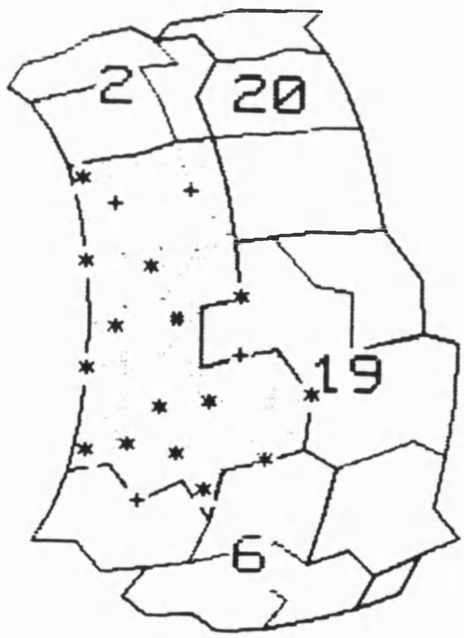


Figure 8.4 Typical Surface Patch

vertices.

One of these conditions will always be satisfied. When the bridging points to all adjacent patches have been found the list of adjacent groups is ordered on the basis of the angle between the group centre.

The algorithm was written in Fortran 77 within the program SURFACE. It is rapid and quickly outputs a file containing the surface point data. It has been tested upon different analytical and commercial shapes and no problems have arisen. A typical output for a patch is shown in figure 8.4.

8.3 Generation of Links

In order to reduce on-line processing and data storage when selecting paths around the points of a polishing patch, a series of links are calculated. The abrasive head moves around the surface using a travelling salseman algorithm to randomly follow the links. The randomness of the motion reduces continual machining of the same areas, as a second visit to a patch will follow a different path.

The lateral nature of the previous polishing patches caused the links to lie along the minor curves of the component, and the resulting motion caused faceting of the component. Some links were created around the major curves but they could not be selected on-line as the robot has no knowledge of the component geometry. Therefore all of the links must be created with regard to the local geometry of the component. Additionally the previous movements were small and localised, and tests showed an improvement in surface finish could be obtained by making them longer.

The linking therefore has a number of objectives:

i) Links that follow the major curves of the component;
ii) Long links; and,
iii) Creating a number of links for each surface point to assist in the randomness of movement.

A measurement of the effectiveness of a link can be obtained from the distance between the two surface points and the angular difference between the surface normals.

To prevent repeated machining, links should not intersect nor should they pass close to another vertex. The creation of large links around the surface will therefore restrict the number of links available, and so a limitation in size and curvature will be needed. Similarly surface points with small angular difference should not be considered for linking.

The links were originally constrained to be within the boundary of the patch. With the larger convex polishing patches this restriction was removed as the overlap of the belt removes the error in position and additionally assists in the blending of one patch into its neighbours.

8.3.1 Algorithm

The algorithm considers each patch independently. It first creates a node list linking all vertices. Considering one surface point (node) all connected nodes are tested and if the difference between the two D.C.'s falls below a minimum angle, the node is removed from the list. A distance/angle value is calculated for each node and the list ordered in two sections. First those below the maximum angle and then those above.

Then for each node in the patch, the 'best' link is selected from the list and if it does not:

i) Pass within 3 mm. of another node; or
ii) Intersect another link.

Then the link is selected and stored . If it fails, it is removed from the list and the next node in the list is considered. When all links have been linked once, the pass is repeated and if a node has less than the minimum required number of links, the next node in the list is tested until a single link is added. The loop repeats until all nodes are connected to the minimum number of links or there are no valid links left. The central node of the group is finally tested to ensure that it has enough links.

A surface point can have any number of links, and as long as there is at least one it can safely be incorporated into the database. Although this will not be an ideal condition as it could cause repeated machining of the surface.

8.3.2 Implemenation and Results.

The linking program POLINK is implemented on the VAX 730 written in Fortran 77. A graphical output of the different stages of the linking process is given, to assist the operator in the selection of the linking criteria. The user can control the process, by specifying the minimum and maximum angles between valid nodes, the minimum number of links to each node, and the central node, and the criteria for ordering the links.

The criteria are calculated from the product of the variables ANGLE and DIST obtained from one of the following:

i) ANGLE = alpha
ii) ANGLE = COS(alpha)
iii) ANGLE = 1.0/alpha
iv) ANGLE = 1.0/COS(alpha)
v) DIST = d
vi) DIST = d
vii) DIST = 1.0/d
viii) DIST = 1.0/d

Where:

alpha = Angle in radians between the two direction cosines; and,
d = Distance between the two points in cartesian coordinates.

Through testing on different analytical and commercial shapes the best results for links around the major curves were obtained with the relationship:

$$\text{Ordering value} = \frac{\text{Distance in cartesian coordinates}}{\text{Angle in radians}}$$

The minimum considered angle was consistently found to be around 5.0 degrees whilst the maximum varied between 20.0 and 40.0 depending upon the curvature of the component. The typical output is shown in figure 8.5 illustrating the successful nature of the linking around the major curves.

8.4 Selection of abrasive head position.

The new robot configuration has two different abrasive positions depending upon the local curvature of the component. For concave patches on the component there is a 50 mm. diameter contact roller, whilst for convex patches there is a suspended belt. To select which position is to be used the system must first identify whether the patch is convex or concave.

8.4.1 Testing for concave patches

Although this task can be performed relatively simply graphically it is not as straight forward computationally. The major technique to achieve this is by considering the surface triangle patch as a 3-D convex hull. The convex hull in 2-D can be considered as follows (61):

> Given an n-sided polygon a rubber band is placed around the boundary (8.6). The polygon defined by the rubber band, the smallest surrounding polygon is the convex hull. If all of the points defining the polygon lie on the convex hull, then the polygon is convex.

On a 3-D shape the points can be considered as being covered by a rubber sheet. A rapid simple algorithm was used to test the surface patch to see if it is its own convex hull.

i) For every triangle in the patch construct the plane that it lies in by using the triangles surface normal and one of its vertices.
ii) For every vertex within the patch except the ones connected to the triangle, calculate the relative distance to the

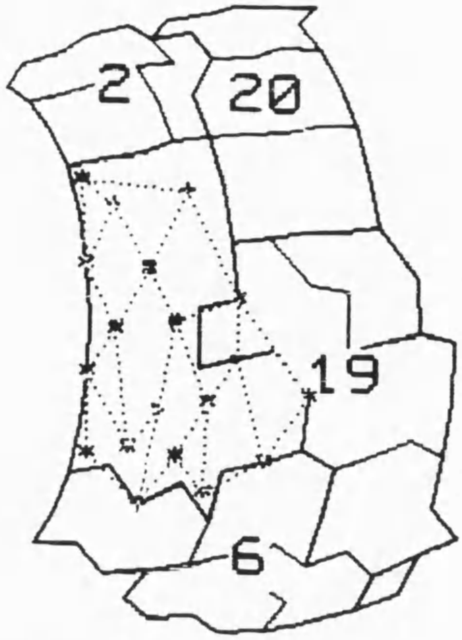


Figure 8.5 Typical Linked Patch

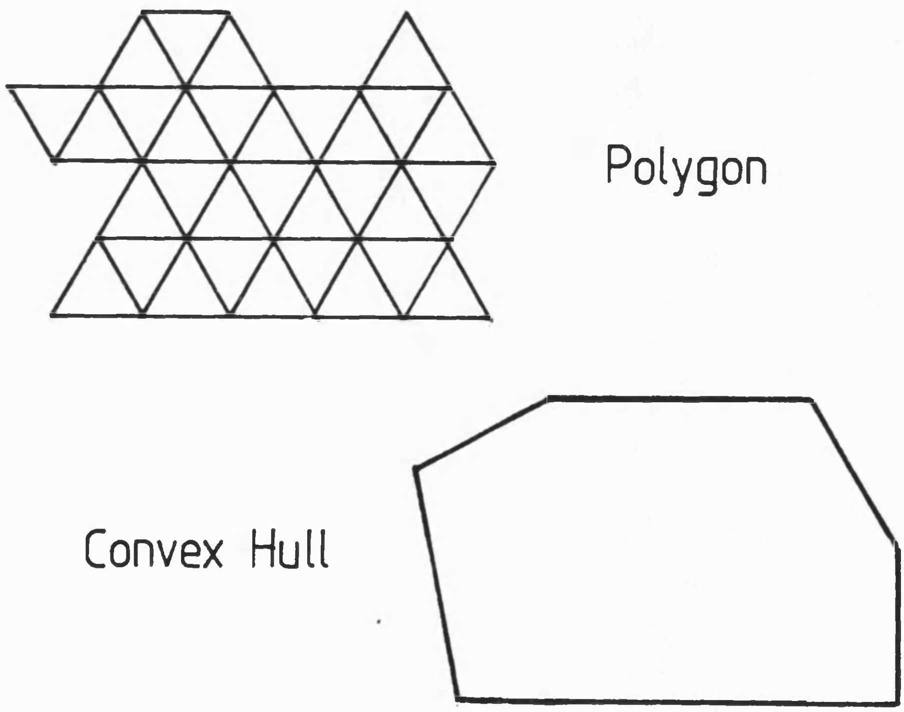


Figure 8.6 Convex Hull of a Polygon

plane.

iii) If a point is above the plane then the surface is concave.

8.4.2 Calculation of position of abrasive head.

The previous test decides if the abrasive head positions the roller or the belt in contact with the component. The roller position is calculated using the software developed by S.Jenkins (sec 3.4.3). This solves the position for six DoF, by calculating the best conformity for the roller to the surface for different orientations, when the abrasive head is aligned along the surface normal. When the suspended belt is used, only five DoF are present and a new criterion is created.

The belt is orientated so that it is orthogonal to the surface normal, at a point 60mm. along the belt from the contact roller (fig 8.7). A vector def specifies this direction away from the belt. The belt is inclined so that the angle between def and the direction of the arm, specified by vector pqr, is 78 degrees. Knowing that the vector abc that describes the orientation of the arm is perpendicular to both vectors def and pqr, and that there is no yaw in the abrasive head, the position can be calculated.

The backoff vectors and the points on the safe surface are also calculated at this stage. After calculation of all of the surface, safe and inspection points, they are transformed into the coordinate system of the robot. For further details see appendix A.

The calculations are all performed by the program ARMPOS. It is flexible as it allows the modification of the roller size and position from the roller to point of contact on the suspended belt. It has an additional task as it stores whether a surface is convex or concave for on-line path planning control. As the abrasive head can only move to an adjacent group, if it is machining with the same position on the head. The transforms into the robot coordinate system are performed by the program 3DTO5D. If a position cannot be transformed because it is out of the robot working envelope, then the database is marked to indicate the failure.

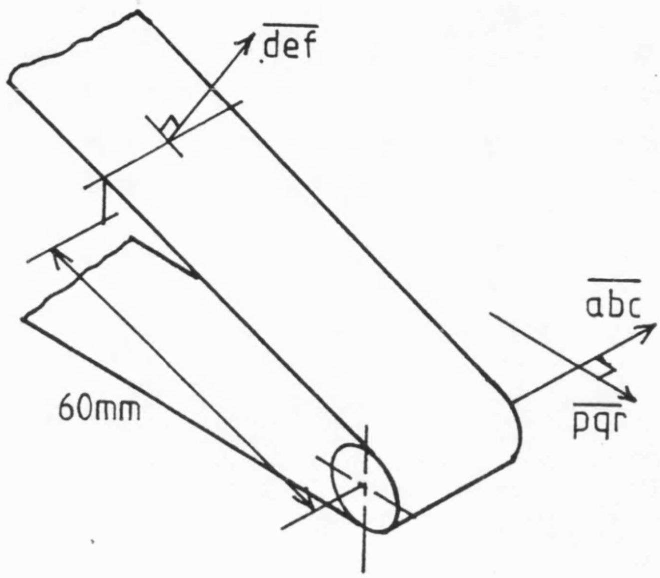


Figure 8.7 Vectors Used to Calculate Abrasive Head Position

8.5 On-line Implementation

The on-line strategy was developed to include the new polishing patch ideas. Modifications to the control strategy occur within the path planning, as the system must recognize the different abrasive head positions, and plan motions using the component geometry. To enable this, the global path planning was changed for the different type of moves.

When polishing, the abrasive head only moves to a free adjacent group if it has the same geometry i.e. both patches are convex or concave this prevents severe collision problems occurring, as the system changes from suspended belt to the contact roller. If the only free patch is of a different geometry, then the move proceeds via the safe surface.

Adjacent patches are ordered and stored in the database on the basis of the difference in angle between their respective direction cosines, and their respective surface geometry. To select an adjacent patch, the controlling program searches the adjacent patch list in order, selecting a group if it has not already been polished and if it has the same geometry. If a patch is not found then the nearest un-polished patch is selected regardless of geometry. The robot continuing its move via the safe surface.

The criterion for selecting the next inspection group is the same as that for a polishing move via the safe surface. The nearest un-visited patch is selected by calculating the shortest move in terms of time. This is found by identifying the maximum move of a single axis in terms of robot coordinates and multiplying it by the correct delay value.

After a patch has been polished all of the constituent inspection groups are marked for the inspection cycle. During the inspection cycle if any group fails the thresholding tests then the parent patch is marked for polishing and all other inspections groups are marked as failed. This reduces the time of the inspection cycle.

A travelling salesman algorithm was installed within the middle processor to perform the local path planning around the polishing patch links. The algorithm is given a start and exit node at either the centre of the patch or one of the bridging points and works as follows. The algorithm marks each point with value corresponding to the number of links that it is away from the exit point. The route is started from the entry node. It identifies which connected node has the highest label and this is selected as the next node in the path. If more than one node has the same label then one of them is selected randomly. This prevents the same path being followed each time the patch is visited. The new nodes connected nodes, which have not yet been visited, are then considered in turn. If there are no adjacent unvisited nodes then the algorithm ripples out until a node is found. Again the highest labelled node will be chosen. The route to this node is easily determined. The process continues until 80 % of the surface points have been considered and then the route is found to the exit. An example is shown in figure 8.8

The strategies have been incorporated on the triple processor 11/23 system in the programs TOP, MIDDLE and BOTTOM. The positional accuracy was tested and after verification of the movement strategies the entire system was commissioned. The next chapter will discuss the effectiveness of the total system considering the off-line data creation, and the on-line testing of two components.

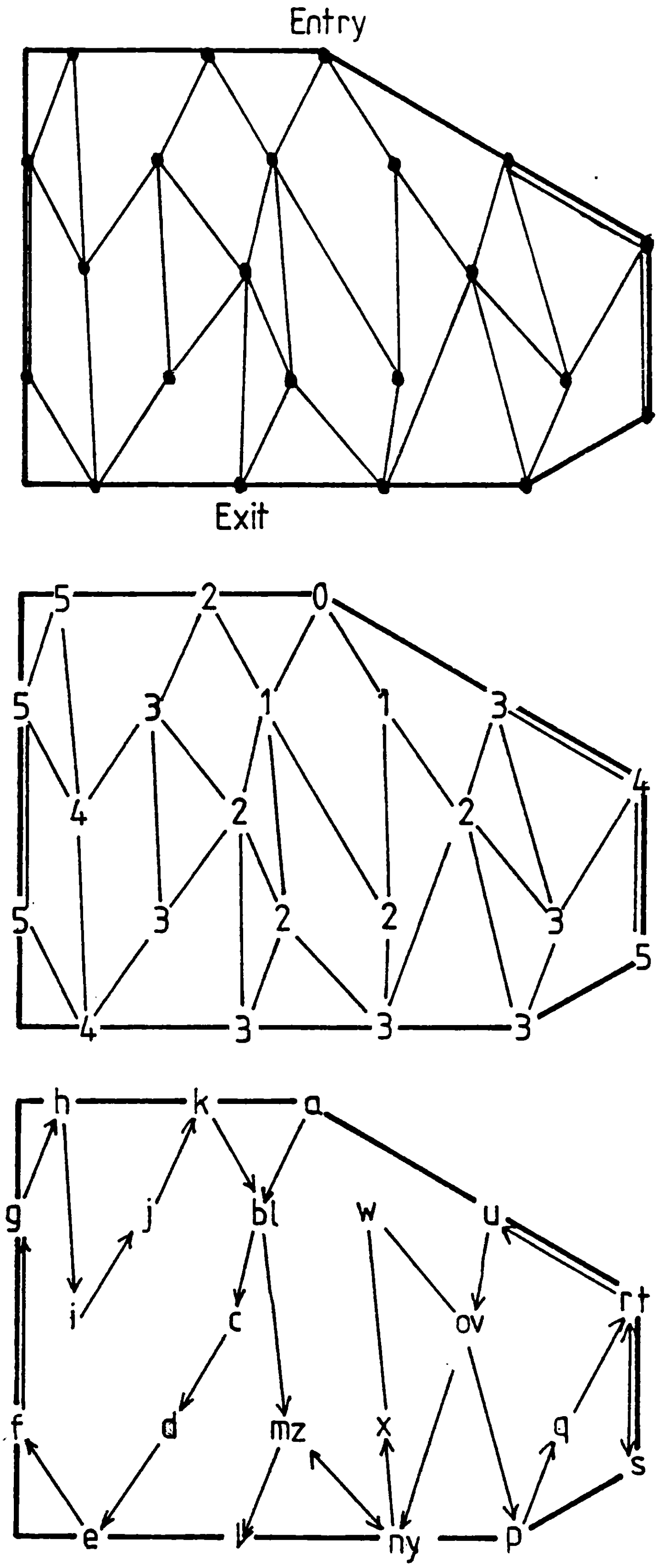


Figure 8.8 Travelling Salesman Algorithm

9. DISCUSSION OF THE SYSTEM PERFORMANCE

For the first time the entire system was commissioned, performing both inspection and machining cycles. A machining cycle was successfully completed on a doubly curved component. A considerable improvement being obtained, when compared with the previous machining tests, both with the polishing cycle and the resulting surface finish.

This chapter evaluates the mechanical system, and then describes the two different components used in the commissioning tests, and then presents the results obtained from the machining cycle. It then proceeds to evaluate these results with regard to the original specification by considering the following factors:

i) Realisation of the overall system concept;
ii) Mechanical efficiency of the grinding process;
iii) Component surface conditions;
iv) Cycle times; and,
v) Accessibility and component complexity.

9.1 Basic Robot Parameters

Before describing the effectiveness of the robot system in finishing a component, a brief assessment is made of the mechanical system. Three factors influence the robot performance:

i) Positional accuracy/repeatability;
ii) Axes feedrate; and,
iii) Working envelope.

An accuracy of 1 mm with a repeatability of 0.5 mm was originally specified within the cartesian reference frame (appendix A). The repeatability was achieved on all axes, especially by using the harmonic gearboxes on the rotary axes. The positional accuracy of the robot had two limitations, the backlash within the drives and the stiffness of the robot frame.

The backlash predominantly affects the linear axes and is of the order of 0.2 to 04 mm. The 9 to 11 steps of backlash within the rotary axes translates to approximately 0.022 of a degree. The movement algorithm compensates for all of the known backlash.

The simple robot construction is based upon light aluminium box sections on a fabricated steel framework. This construction was chosen to allow the driven elements of the robot to be constructed as lightly as possible. The effect of this is that the individual arms are flexible. This had little effect on the accuracy of linear motions on the inspection and polishing heads, although a slight overshoot occurs when the heads stop, due to lack of de-acceleration at the ends of the move. This had an undesired effect at the beginning of a machining move when the head moved in from the safe surface at it produced momentarily an excessive machining condition. To compensate for this, all *start* moves were slowed down to 40% of maximum. On the workhead axis the lack of stiffness caused large oscillations in the pitch axis, as when under load from grinding, the head would deflect away from the abrasive belt. Although the system has a positional accuracy of under 1 mm for unloaded conditions, these combined effects produces errors of the order of 5 mm.

The slew rates of the motor have a direct effect upon the control of the machining operation. The adaptive control system produces a constant machining intensity, i.e. a constant metal removal rate, whilst maintaining the component geometry. The removal rate is the product of the feedrate and the depth of cut, but to maintain the geometry, the depth of cut is kept low, therefore a high feedrate is needed to maintain a high cutting intensity, which is easier to measure and control. On the system the motor slew rates of all axes fell below the desired levels. In particular, the rotary axes are only 7/16 of the original specification, due to the introduction of harmonic drives. The motors were capable of being driven at a higher stepping frequency, but the low power output of the drive cards prohibited this. additionally under load the pitch axis lost steps when raising the component, and had to be driven at a lower step rate.

The working envelope of the robot was modified by the introduction of the new machining head configuration. A typical component occupies only a small portion of the effective working area (fig 9.1), and the offset from the centre line of the machining

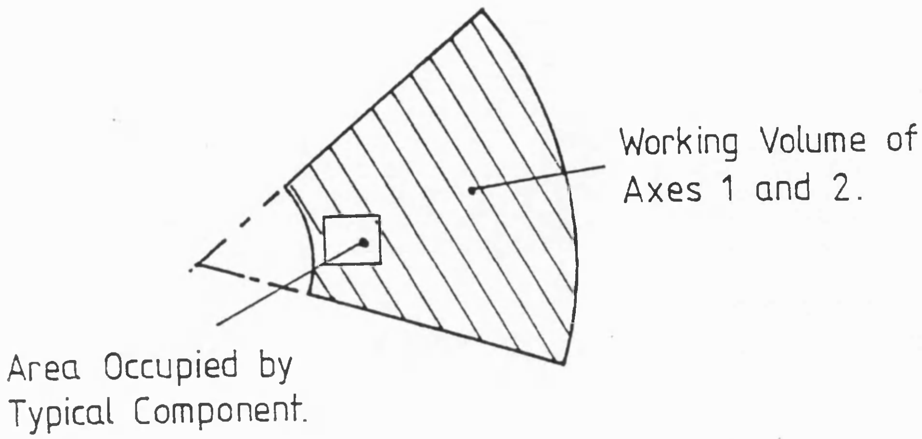


Figure 9.1 Working Volume of the Workhead Axes.

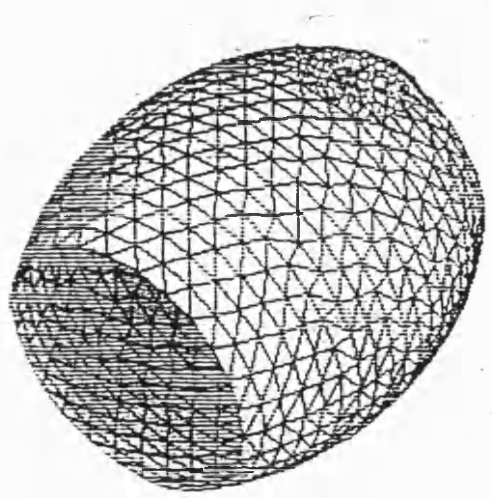


Figure 9.2 Triangulated Model of the Barrel

head rotary axis, due to the suspended belt, caused the component to be moved further towards the bottom limits of the axes. Additionally the moving of the abrasive position away from the roller reduced the linear travel of the machining head. This resulted in a number of components being partially outside of the working area.

A further factor in reducing the number of points the robot could access, is the reduction of the number of degrees of freedom down to five. Even allowing for the workheads to take any orientation about a patch or group, a number of them could not be accesses due to collision and positional problems.

In all, mechanically the system falls below the desired specification, due to limitations in the initial design and modifications required to correct faults in the drive system and machining configuration. Although the existing system is limited, there is still sufficient flexibility to under go the commissioning tests using the two selected components.

9.2 Testpiece Specification

All previous tests upon the system were performed with a simple cylindrical component. This singularly curved surface was chosen to reduce modelling errors and collision problems. In order to evaluate the system further, complex doubly curved components must be used. Two testpieces were therefore chosen. They were a commercial component, a tap, and a machined doubly curved component, a barrel. The modelled testpieces are shown in figures 9.2 and 9.3. They were chosen for the following reasons.

i) Both testpieces are doubly curved and represent a number of features found across the range of components supplied by Walker Crossweller;
ii) The simple geometric shape of the barrel can be generated by a mathematical model. The triangulated mesh will therefore not be as susceptible to errors due to inaccuracies caused by the triangulation package and coordinate measuring:
iii) The barrel component geometry reflects the large flatter

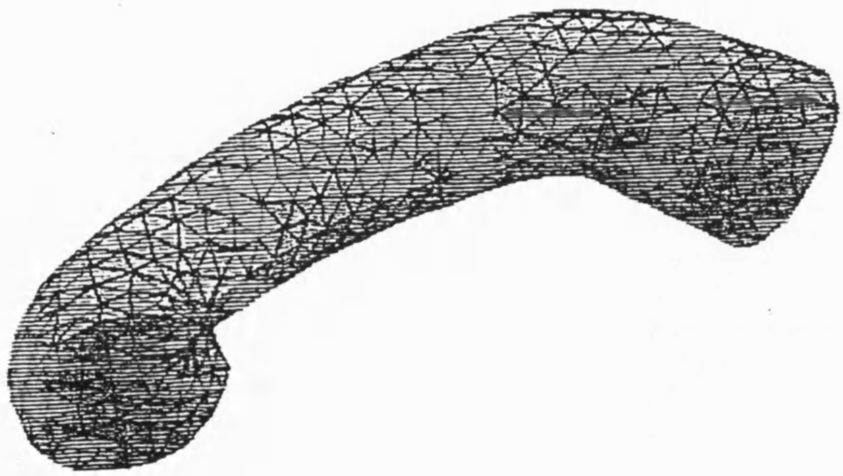


Figure 9.3 Triangulated Model of the Tap

surface typical of the other components in the Crossweller range;

iv) The component feedrate and hence cutting intensity will be higher due to the large specimen radius, i.e. 40 mm to 25 mm.;

v) The tap is one on the specific components selected by the company for automatic surface finishing. The component contains a high degree of curvature and was felt to be one of the more difficult components to machine. Thus any inadequacies in the system will be highlighted; and,

vi) The tap is also a complex shape which is made up of both convex and concave regions, which will result in both convex and concave patches.

Two databases were created off line using the new polishing patch strategy. The initial creation of the triangulation model differed between the two components. The barrel model was created mathematically producing a regular ordered pattern (fig 9.2), whilst the tap model was created using the coordinate measuring machine and the triangulation package (fig 9.3). The specification of the two databases is shown appendix E. After initial tests confirmed the correct positioning of the abrasive and inspection heads with respect to the component, both components were machined.

9.3 Test Results

The results of the machining are presented in terms of:

i) General assessment of the operation;
ii) Amount of surface covered;
iii) Cycle times (machining and inspection);
iv) Surface integrity;
v) Secondary and primary surface finish; and,
vi) Dimensional integrity.

9.3.1 Barrel

The robot coped well with the barrel geometry, although not all of the surface could be machined as some points were outside the working envelope. Of the 23 polishing patches, the robot successfully machined 16, 60% of the testpiece surface. The remainder were outside the working envelope, in both the machining and inspection cycles. No local or global collisions occurred during the machining cycle.

All machining movements followed the directions of the major curves. The typically meant a rocking motion of the suspended belt around the barrel axis with an amplitude of between ten and twenty millimetres. No problems occurred with misalignment between the belt and the surface. The oscillation of the abrasive head about axis 6 (fig 3.1), seen with the previous polishing strategy, did not occur. The robot appeared slow during the machining stages, even with the increased feedrate due to the larger radius. This is mainly due to the speed rate of the revolute axes.

There was no discernable difference between the robot machining within a patch, to when it moved to a new patch. The inspection cycle takes typically three seconds to move and perform the first stage of analysis (2). The total inspection cycle taking one to two minutes depending upon the initial state of the surface.

Within a complete cycle the system typically removed the major defects on the first machining cycle. Removal of persistent defects took and extra two or three machining cycles. around the edges of the component, the system identified defects were none were apparent. On no occasion did the inspection pass the component after only one machining cycle.

The finish component is shown in figure 9.4. The surface integrity was generally good, with an even removal of material over the entire surface of the component. The general shape of the component was well maintained, with no portions of the surface left unmachined between neighbouring groups as occurred previously.

Generally the surface finish was of a high degree with defects

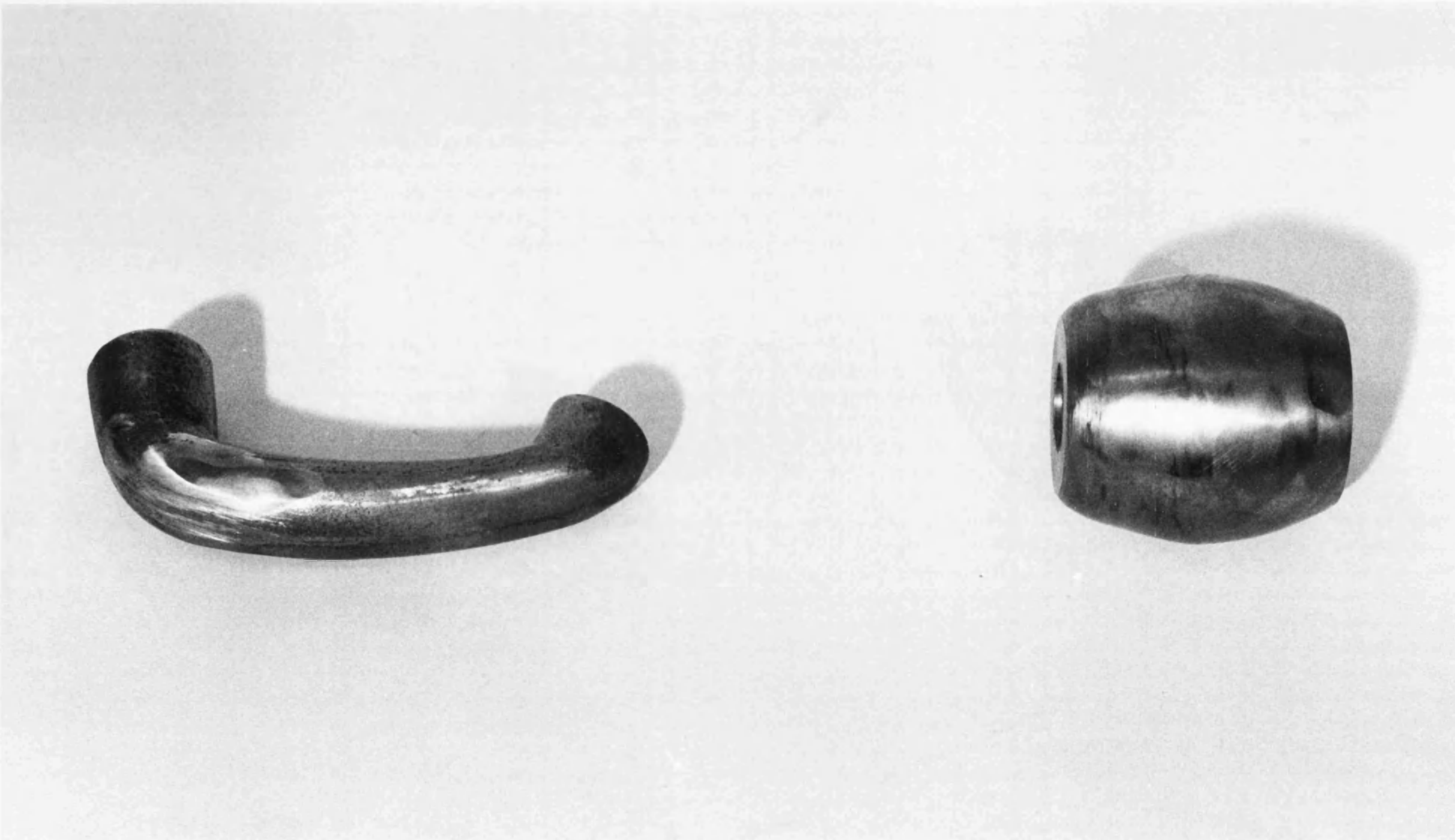


Fig 9.4 Tap & Barrel

effectively removed. Ripples in the surface occurred at the extremity of the machining move, where the abrasive head changes direction whilst moving near the edges of a patch. They are only removed, if the robot moves across this point in order to reach a neighbouring patch. They also occur, when a single patch that can only be accessed via the safe surface is machined.

The dimensions of the component were well maintained, although the metal removal rate of high. The only area were excessive machining seemed to occur was at the edges of the component.

9.3.2 Tap

The tap cycle was limited due to the number of inaccessible patches caused by collision or positional problems. Of the twenty five patches only seven could be successfully accessed. The majority of the patches failed due to the inspection position being outside the working envelope. The few groups covered both the concave and convex portions of the tap. The limited cycle was only executed on the elbow and top of the tap. Through trying to increase the machining cycle, by ignoring the inspection cycle, most patches failed due to local collisions. Parts of the abrasive head interfered with the component, and unwanted machining occurred between the abrasive belt and the workpiece or the workhead when machining with the contact roller.

The scurfing movement, although following the major curves of the component, did not always follow an ideal path with regard to the belt direction. Ideally the direction of movement should lie in the same direction as the major axis of the belt. When on top of the tap it in fact lay directly across it. This occasionally resulted in the abrasive belt being dragged off its guide rollers forcing the machining process to be aborted.

The patches on the tap took longer to be machined than those on the barrel by 10 to 15 seconds, and the machining operation appeared to be more severe. The relative position of the workhead to the surface oscillated more during the machining operation than with the barrel, whilst the feedback system was trying to maintain the constant cutting intensity.

As only a limited portion of the tap was machined, little evaluation of the surface finish could be made (fig 9.4). Generally the machining intensity was greater than that with the barrel, and so the tolerance limits for grinding were dropped. The operation successfully removed all defects, although the rippling effect caused by the polishing head changing direction was more severe. There were times when the grinding system stalled, and to reduce this the belt tension was slackened. Greater oscillations between the abrasive belt and the component were seen to occur with the drop in belt tension and reduction in grinding intensity, making continuous control of the process more difficult

9.4 System evaluation

The first section considers the degree of success in achieving the overall concept of the robotic system. The next four sections deal with the effectiveness of the system in producing the desired component with the correct surface finish in the desired cycle time.

9.4.1 Realisation of the overall concept

In the early analysis of this task, a third generation robotic system was selected as the solution to this complex machining task. From the commissioning tests, it was apparent that although the complexity of the robotic system was not sufficient to accommodate all of the geometries supplied by Crossweller, all of the required elements needed were successfully implemented within such a system. The main factor in failing to reach the desired goals was the mechanical hardware, the control and various software strategies rarely failed to accommodate the complex, shapes, the regions eventually being rejected for collision or access problems. A controlled machining operation was achieved that was considerably more complex than any other existing system, through integrating two levels of control. One based upon the actual grinding conditions and the other through in-process inspection of the machining results.

The overall concept worked well, with the idea of off-line path planning allowing real time decisions to be made to machine the complex geometry components. Decisions were made with relatively little sophistication in computing power or memory storage. In particular, routes were selected through consideration of local component geometry.

The vibration monitoring system provided a simple and effective way of monitoring the machining intensity. Coupled with a detailed knowledge of the component, paths were successfully modified to allow controlled and even machining of the complex geometries.

The main problem with the system, as has been previously stated was the mechanical hardware. Limitations were found with introducing the new abrasive head, as well as basic problems due to motor power and mechanical stiffness of the robot. These contributed to the system failing in some of its objectives, but due to their nature do not refute the overall ideas behind the system. The concept of splitting the system into a number of work heads worked well, but the small working volume, coupled with the limited movements of the workpiece head, meant that the complex geometries could not be completely machined. A major problem with the new abrasive head was due to the loss of a degree of freedom, but this had been identified at the design stage, where it was felt the lack of versatility of the system would be compensated be enabling the system concepts to be proven.

The single limitating factor that is not easily corrected in the system concept, is the collision detection and avoidance. A factor compounded by both the difficult geometry of the tap, and the limited movement of the robot. Whilst the idea of the global safe surface was a success, local collisions frequently occurred with the complex shaped testpieces. The idea of a component model based control, combined with the robot geometry, allows collision detection to be identified at the path generation stage, but as has been previously stated this can only occur at discrete points, and how the system responds when it detects a collision, causes major problems at the path planning stage. During the commissioning tests collisions were also identified between different workheads.

9.4.2 Mechanical efficiency of the grinding process

The metal removal rate of the new grinding process was very good. If anything it was actually too high. To improve the control of the process, there are three suggested modifications:

i) Higher slew rates. The low slew rates of the stepper motors produced a low feedrate, and so the adaptive control of the abrasive process has to be very precise to ensure that there is only limited metal removal;

ii) Increased power for the grinding motor. The power of the abrasive belt drive motor is not sufficient two overcome all the friction in the system when the belt is at an optimum tension. To ensure against the belt stalling, the tension had to be dropped and therefore the belt became more flexible resulting in it rippling whilst being driven. The rippling causes the local belt tension to vary and therefore the grinding normal force to oscillate. To reduce the effect of these oscillations the response rate of the system had to be dropped; and,

iii) Increased stiffness in the robot framework. The lack of stiffness in the system causes the arm to vibrate and oscillate, causing the grinding normal to vary.

The grinding intensity appeared higher whilst machining the tap than that for the barrel. The main reason for this is believed to be the grater curvature of the tap causing lower physical contact between the belt and the component resulting in fewer particles exciting the component. For the system to maintain the same grinding intensity the normal force would have to be increased resulting in excessive material removal. For the test the normal force was maintained by dropping the intensity but this resulted in greater oscillations of the system.

The new abrasive head proved very effective whilst machining the barrel, the suspended belt easily adapting to the doubly curved surface. The contact wheel was used solely on limited portions of the side of the elbow section of the tap. It did not prove very successful. The high curvature of the tap resulted in only limited contact with the 50 mm roller, creating a much higher local machining intensity than desired.

9.4.3 Component Surface Condition

The barrel finish is mainly evaluated here as only limited machining took place on the tap. The concave portions of the tap could not be successfully accessed and so no evaluations could be made of the finish. On the top and elbow of the tap where it was machined by the suspended belt, the finish obtained was comparable to that on the barrel and comments made refer to both components.

There is a significant improvement in the finish obtained by the new planning system over the previous tests. Although it is not considered sufficient to replace completely the human operator, it does successfully perform what is known as a first scurf, where the entire surface is cleaned and persistent defects are removed. The finish is deemed evenly machined but not good enough for plating. This is not a measure of the surface finish produced, but the effect the machining cycle has had upon the geometric integrity. The system produces a slight wavyness in its machining that needs to be completely removed by a human operator. This wavyness cannot be successfully identified by a inspection system and required the versatility of the human eye.

The primary surface finish was very good with an even finish achieved by the path planning algorithm over the majority of the surface (fig 9.4). Occasionally using the simple selection algorithm, a single patch was left isolated causing it only to be accessed from the safe surface and not blended into its neighbours. A more significant algorithm may be needed based upon a similar form to the travelling salesman algorithm used within a patch. Previous problems of unmachined areas did not occur. The only major problem with the surface finish is that slight ridges can occur in the surface at the extremities of the machining move, when the abrasive head changes direction sharply. To prevent this the intensity of the operation would need reducing when moves get close to a surface point. The secondary finish is of a high degree needing no further work to remove surface defects.

The distribution of surface points was successful in that all of the component was covered without excessive repetition. The distribution of points around the complex regions of the tap were higher than other areas because they were represented by many undersized triangles, whilst large flatter regions occur on the the top of the tap and the barrel.

The edges of the component were the only areas to be excessively machined. This was due to the limited contact between the belt and the component when the belt over hangs the edges of the component. This is appears as a low cutting intensity. Similar effects were noticed with the tap where there was a high degree of curvature. In a complete system the amount of contact that occurs between the belt and the component must be used to set threshold levels for machining. It is easily derived from the computer model and knowledge of the belt orientation.

The other region where excessive machining occurred was on the edges of the component, where the inspection system falsely identified defects. On investigation the cause was identified as incorrect position of the workheads causing the mask to be misaligned and portions of the background interpreted as defects.

The success in machining the barrel is particularly encouraging as the majority of the newer components from Crossweller have larger flatter surfaces as opposed to high degrees of curvature.

9.4.4 Cycle Times.

The cycle times for the system were below specification (appendix A=). The main reason is the low slew rates caused by the initial problems with the gear boxes. The rotary axes in particular are considerably slower than the specification due to the inclusion of the harmonic gearboxes. However even where the original gear ratios remain, the lack of power from the stepper drive cards meant that they could not be driven at the maximum stepping frequencies. The previous position algorithms caused large overheads in cycle times due to oscillations of the abrasive head, with the suspended belt the alignment was much closer. The major contribution to the cycle time, is the response rate of the adaptive control system. To prevent system oscillations, due to variations in the normal grinding force from stiffness and belt tension problems, the response of the grinding monitoring system was dropped. This in turn caused problems when machining with too high an intensity as it dwelled for too long and effectively machined away the problem. After backoff the intensity then becomes too low.

The effect of the cycle time due to inspection fell. This was because originally the total initial time was defined by the number of groups to be inspected, multiplied by the time for a single group. A number of groups now make up a patch so if a defect was found within one of then the system ignored all the others until after the next polishing operation.

There is no noticeable overhead due to computational analysis. The look ahead method for path planning always operated faster than the system moved, and the most significant portion of the program, when considering time, is taken up performing I/I to the operators console. Even the proposed increase in feedrate would not have been faster than the actual analysis, which took two or three seconds to obtain the next path. This allows greater sophistication in the planning algorithm to be successfully implemented if needed.

When moving around the global safe surface, further increases in cycle time could be obtained. Currently components are

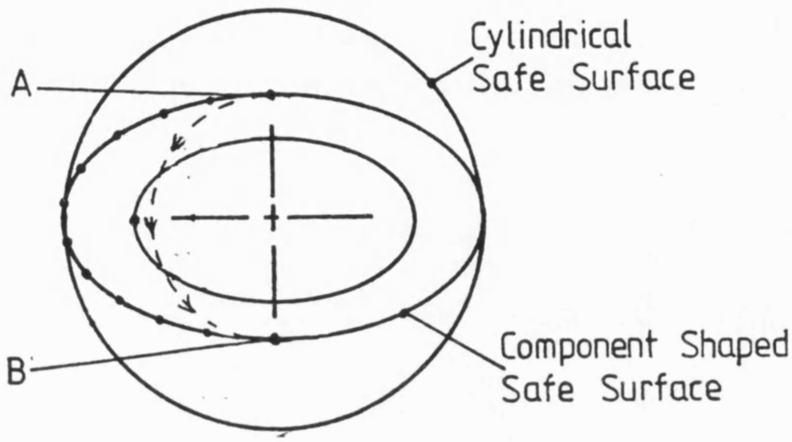


Figure 9.5 Reprresentation of Component Safe Surface

encompassed by a cylinder that is aligned to the centre of axis five (fig 9.5). This resulted in large movements on one side of the component when moving to and from the safe surface and around the surface from patch to patch. These moves were considerably greater than was needed. An alternative approach is to create a surface that is simply an expansion of the component surface, (or convex hull of the the component surface). This would reduce movements to and from the component but the simplicity of planning paths would be lost, as direct move from point A to B would result in a rotation causing a collision. Instead the path would need to be along a set of intermediate points that correspond to the patch centres.

9.4.5 Accessibility and Component Geometry

The robot could not cover all of the surface for either the barrel or the tap. With the barrel some surface points furthest from the chuck were outside the working envelope of the system. This problem is mainly due to the redesign of the workhead and is not considered a significant fault with the system. Of the rest of the component, the system had no problem positioning the inspection and abrasive heads without collision. The tap was unfortunately far less successful, again most problems were due to positions being outside the working envelope. The most significant problems occurred with the inspection system on the undersized of the the tap. On investigation although the effective working volume of the robot is quite large when compared to the component, most operations occur in a relatively small area near the limit of axis two. One cause if this is the modifications made to the chucking in order to accommodate the load cell behind the component.

To enable better access to the component, more than one chucking point may be needed on each component. Chucking was originally identified as a major consideration in machining castings (12), and observations from this project confirm this.

When introducing the new abrasive head configuration, the modifications made to the system included the removal of a degree of freedom. Not only does this affect the access to the component, but on portions of the tap the abrasive belt was unable to align itself across the direction of major curvature, producing greater contact between the belt and the component, and thus a higher machining intensity. The author believes that even if this single extra degree of freedom was present, then this would still not be significant in enabling more of the tap to be accessed. Pitch and yaw axes would be needed at the end of axis two before the chuck to ensure that all of the component could be reached. The system has only served to show that five degrees of freedom in the current configuration, will only be successful on doubly curved shapes based around a single axis, although this does cover a wide variety of components.

The complexity of the tap geometry will always cause problems due to collision, and a complete investigation of the methods for detection and avoidance must be completed.

9.4.6 Summary

To summarise the results of the commissioning tests, the basic observation is that the original concept of an intelligent robot performing a surface finishing task upon complex components, can be realised by employing third generation robotic techniques.

The barrel component was successfully machined with no path planning or collision problems. The surface was of a high standard, but due to effects upon the geometric integrity, it is not regarded sufficient to completely remove the operator from the scurfing environment. It is nevertheless a significant improvement upon current surface finishing techniques.

The complicated geometry of the tap caused local and global collision problems, although it is believed these are mainly due to an inadequate number of degrees of freedom within the workhead. The inability to machine the concave portions of the tap was a major limitation for machining complex components. This system will only be limited to convex, or gradually concave components, that can be accesses with either the suspended belt or a large compliant wheel.

10. CONCLUSIONS

In this thesis, a novel control system has been developed for integration within an intelligent surface finishing robot. The robot performs a grinding operation over the surfaces of complex brass die castings. The system incorporates features to be found within a third generation robotic device. This includes in process machining monitoring, and path planning for dealing with complex geometry components. Combined they integrate within a system that is capable of identifying and removing persistent defects from complex shapes.

The robot system is based upon three different workheads, one to hold the workpiece, a second containing the abrasive grinding system, and a third for visual inspection of the component. To control successfully the process a strategy had to be developed for controlling the machining operations. This led to three specific items of research:

i) A monitoring system for controlling the grinding operation:
ii) Development of an abrasive head configuration; and,
iii) A machining strategy.

The monitoring system is based upon induced vibrations that occur from effects of the machining process. A piezo-electric load washer mounted within the chucking arrangement, detects vibrations caused by resonance and acoustic emission, due to the grinding operation. These vibrations occur typically above 3 kHz., and are converted into an electrical signal, giving a linear measure of the current grinding intensity, that is independent of the point and direction of contact, of the abrasive head. This signal is then used to control the grinding intensity, through integration with the movement strategy.

A major problem was found with the original design of the abrasive head. In this an abrasive head was run over a small contact roller. This roller was too hard and had little conformity resulting in a poor surface finish. The abrasive head was developed combining two different machining areas for addressing both convex and concave regions of the component surface. The main machining area is a belt suspended between two rollers. The conformity of the belt provided a large area of contact when machining. This allows the machined areas to be blended together, resulting in a high degree of surface finish, A contact roller with a high conformance was used for any concave portions of the surface. This had limited success as the 50 mm. diameter roller had difficulty accessing highly curved regions.

A major factor established in obtaining a good surface finish is the direction and length of movement of the abrasive head. Due to the complex nature of the component geometry, a model based approach was used where a mathematical model, representing the component surface, was used off-line to generate sets of paths for machining and inspection. Originally a strategy had been proposed to divide the component surface into individual areas for machining and inspection. These areas assist in relating the inspection and machining operations together, and allow controlled viewing by masking out highly curved areas of the component. This reduces complications due to oblique viewing or uncontrolled lighting falling on the surface.

Initial testing showed that these regions, typically 20 mm long and 10 mm wide, were too small for machining purposes. When machining them the system produced a highly facetted surface. through experimentation, it was established that the movements should in fact pass around the major curves of the component, and ideally be 10 to 20 mm long. These requirements were opposite to what was wanted by for inspection purposes, the camera requiring small flat areas. To resolve this conflict, a new strategy was developed that created large surface patches, with a greater distribution of points for machining, and made the inspection groups a subset of the polishing patches.

The on-line control allowed real time decisions to be made for path planning and control of the machining operation, by selecting random paths within the polishing patches which reflect the local surface geometry of the component, and controlling movement between patches upon the same basis.

With this strategy successfully developed, the robotic system was commissioned for the first time. The machining cycle starts with a complete machining operation carried out on the component. The inspection system then views the component looking for any defects. When these defects are identified, a second operation is carried out selectively machining this area. The system was tested using two different testpieces, an analytically generated shape, a barrel, and a commercial component, a tap. Successful machining was accomplished upon the barrel, but the tap highlighted the various limitations within the mechanical system, and problems of collision avoidance and detection.

When machining the component, it was obvious that all of the elements included within the third generation robotic system were essential. Repeated and controlled machining was needed to remove the persistent defects identified by the vision system, and must be included to achieve the desired surface finish. Although only limited machining was carried out, it was apparent that a single pass around the surface would not remove all of the defects. To ensure this by increasing the cutting intensity would result in a a more facetted or rippled surface, whenever the abrasive head changed direction, whilst moving around the surface. Only by accurately controlling the cutting process, can an even surface finish be obtained that does not destroy the geometric integrity.

The system as it stands has only proved that the concept works. The surface finish obtained, when machining a doubly curved testpiece, achieved what is known as a first scurf operation, where defects are removed but further machining is required to maintain the geometry. The finish derived is of good quality, but the surface integrity is altered due to the difficulties of controlling the cutting process with low feedrates. The commercial component, a highly complex object, was not as successful due to access problems and the inability to machine the concave regions. The main problem with higher geometric shapes is not controlling the machining, but a basic problem of accessing all of the complex surface. Although some of the problems could be relieved by the following list, a trade off is needed between the complexity of the components, and the desired surface finish. The main factors hindering the process that can be easily removed are as follows:

i) Increasing the power of the stepper drives or replacing the drive system with a more advanced d.c. servo system;

ii) Installing more effective gearboxes on the revolute axes, or combining these with the d.c. drives that have a higher maximum angular speed;

iii) Introducing two more degrees of freedom within the workhead arm. These should supplement the roll of the axes by introducing a pitch and yaw motion into the system. The current pitch in the arm is actually used more to position the component as opposed to orientating it; and,

iv) Introduction of a more sophisticated chucking arrangement that can hold the component in a grater variety of positions. With the tap it could also locate on the spout therefore giving greater access to the underside of the component.

When the project was first implemented the performance of commercial robots was severly limited. Therefore on both grounds of technical performance and cost, the decision was made to develop a special purpose machine. Now with the advent of new more sophisticated and reliable industrial robots, which allow the user to program directly under a DNC or off-line approach, and also have facilities for the integration of sensory devices, a good argument arises for introducing the techniques used here onto a commercial robotic device. Most of the hardware problems associated with the test rig would be removed by changing the workhead arm for a five or six degree of freedom articulated arm. The ability of controllers to access extra drives, would mean it would be relatively simple to keep the other two arms to provide a grater system flexibility. This would also reduce the need to develop yet another CNC controller for the system.

The author well understands that there is a long way to go before these techniques could be implemented within a commercial system. He would like to suggest areas that are considered important in the future development of surface finishing systems.

i) Collision detection and avoidance. Most applications in this area only consider free roving robots, or test simple pick and place operations. To consider the reaction between a robot and a complex shaped environment is an essential area if further work or installations of surface finishing systems is to be achieved.

ii) The force sensor has only been tested for the one application of grinding. A more reliable function that can predict the acceptable grinding signature, without having to first obtain it form actual machining conditions, will be needed before the system can be considered further.

iii) Integration of the groups and the patch creation with a commercial solid or surface modelling system to allow direct input of data from a CAD system.

iv) The algorithm for generating the polishing patches needs further work on generating more regular and even patches.

The considerations so far have been in how to develop this proven concept into a more reliable and sophisticated system for abrasive machining of castings. Besides the specialised field of scurfing, other cleaning and surface finishing operations could also be controlled by the techniques discussed here, and it is hoped that the methods presented here will be of interest to others in the field of robotics who have have to deal with complex shaped components.

The vibration sensor will respond well in any application where a workpiece is excited by a grinding process, for example within standard deburring and fettling operations. The path planning strategy provides a robotic device with a very simple and fast method for planning motions around a complicated geometric shape. There are obvious applications for path tracing in painting and adhesive laying, and for the much simpler task of polishing or buffing, the path could easily be generated off-line. Particular interest has been shown in the project from different industrial areas, from shoe mould manufacture to foundary operations and turbine blade finishing. It is hoped that the ideas developed in this thesis will be of benefit to these users.

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APPENDIX A - BRIEF SPECIFICATION OF SYSTEM

Components

Components are made from either brass or gun metal

Maximum volume occupied - 180 mm by 75 mm by 100 mm

Weigth - 0.2 to 0.5 kg.

Minimum Radius of Curvature - 8. mm

All components have at least two datum faces and location points which are used for mounting when they are machinined.

Defects

Defects on the component typically cover between 10 and 30 % of the surface.

There are two types of defects. The surface defects such as blow holes or scratches that have an area of 1 to 4 mm square and a depth of between 0.1 and 1.0 mm., and the flash and sprue marks that are partially removed before scurfing but leave a root of 0.4 to 1.5 mm.

The surface is cleaned and all defects are to be removed by abrasive machining. This can be done by abrasive belts, or grinding or flapper wheels the selection will be controlled by access to the component. The surface should be machined by successive passes that have a depth of cut of 0.1 to 0.2 mm at a feedrate of 400 to 1000 mm/min. The surface should not be machined to a greater depth than 1 mm and if a defect still exist then the component should be scrapped.

Physical Limitations on System

Maximum volume for robot - 2 m by 2 m by 1.5 m

Volume for Computer and Interfaces - 2 m by 2 m by 3.5 m

Required working envelope - 0.4 m by 0.4 m by 0.4 m

Positional Accuracy - Linear axes < 1 mm,

	Revolute axes < 0.1 deg.
Positional Repeatability	- Linear axes < 0.5 mm
	Revolute axes < 0.05 deg
Services available	- Three phase 415 V AC, 240 AC, 24 DC, Air supply of 6 bar.

Cycle Times

The following are the cycles times that are needed in order to compete with a human operator. They will not necessarily be achieved on the development sytem.

Initial machining of complete surface	- < 2 minutes
Identification of a defect	- < 10 seconds
Removal of a defect	- < 30 seconds
Total cycle time for a competed component	- < 5 minutes

Computer System

To produce an economical system the on-line computer must be a simple widely available processor. Typically a 16 bit processor that will require limited memory and interfaces. To ease the transportability from the development system a final solution where possible all programming should be done in a standard high level language.

Off-line data base and path creation need not be limited by the same constraints as eventually the robot system should integrate with a CAD/CAE environment. Processing time constraints need not be applied as the component data base is only generated once.

APPENDIX B - TRANSFORMATIONS AND EQUATIONS FOR CALCULATING THE ROBOT POSITION AND CONVERTING INTO THE FIVE AXES COORDINATE SYSTEM.

Calculation of Position

The calcultion of the viewing position and the contact roller is described in detail in reference 2. This section describes the calculations used for the suspended belt.

The surface points are specified as a cartesian coordinate and a vector specifying the surface normal. The position of the abrasive head is calculated as follows. The coordinate reference frame for the robot is shown in figure 3.8 whilst the vectors that define the position of the belt is in figure 8.7.

Using the three vectors abc, def, and pqr the position of the arm can be defined uniquely. The following factors are known.

def is the inverted surface normal vector and is known (1)
def is perpendicular to abc (2)
def is at an angle of 78 degrees to pqr (3)
abc is perpendicular to pqr (4)
The arm cannot have an x component in direction pqr so
element p is zero (5)

def.abc = 0 (cross product of two vectors and 2)
$ad + be + cf = 0$ (6)

pqr.abc = 0 (cross product of two vectors and 4)
$pa + qb + rc = 0$
$qb + rc = 0$ (from 5) (7)

def.pqr = cos(78) (cross product of two vectors and 3)
$pd + qe + rf = \cos(78)$
$qe + rf = \cos(78)$ (from 5) (8)

$q^2 + r^2 = 1$ (from 5)

$$r = (1 - q^2)^{\frac{1}{2}} \qquad (9)$$

$$qe + (1 - q^2)^{\frac{1}{2}} f = \cos(78) \qquad \text{(from 8 and 9)}$$

$$(1 - q^2)^{\frac{1}{2}} f = \cos(78) - qe$$

$$(1 - q^2) f^2 = \cos^2(78) + q^2e^2 - 2qe\cos(78)$$

$$(f^2 + e^2)q^2 - 2eq\cos(78) - (f^2 - \cos^2(78)) = 0 \qquad (10)$$

$$q = \frac{2e\cos(78) +/- (4e^2\cos^2(78) + 4(f^2 + e^2)(f^2 - \cos^2(78)))^{\frac{1}{2}}}{2(f^2 + e^2)}$$

$$q = \frac{e\cos(78) +/- f(f^2 + e^2 - \cos^2(78))^{\frac{1}{2}}}{(f^2 + e^2)} \qquad (11)$$

$$r = \frac{(\cos(78) - qe)}{f} \qquad (12)$$

now to solve for abc

$$a^2 + b^2 + c^2 = 1 \qquad \text{(Normalised vector)} \qquad (13)$$

$$qb = -rc \qquad \text{(from 7)} \qquad (14)$$

$$q^2a^2 + q^2b^2 + q^2c^2 = q^2$$

$$q^2a^2 + (q^2 + r^2)c^2 = q^2$$

$$q^2a^2 + c^2 = q^2 \qquad \text{(as } q^2 + r^2 = 1\text{)}$$

$$c = q(1 - a^2)^{\frac{1}{2}} \qquad (15)$$

$$qad + qbe + qcf = 0 \qquad \text{(from 6)}$$

$$qad - rce + qcf = 0$$

$$qad - (re - qf)c = 0$$

$$qad = (re - qf)c \qquad (16)$$

$$qad = (re - qf)(1 - a^2)^{\frac{1}{2}}q \qquad \text{(from 15 and 16)}$$

$$ad = (re - qf)(1 - a^2)^{\frac{1}{2}}$$

$$a^2(d^2 + (re - qf)^2) = (re - qf)^2$$

$$a = \frac{re - qf}{\sqrt{(d^2 + (re - qf)^2)}} \tag{17}$$

$$c = \frac{adq}{re - qf} \tag{18}$$

$$b = \frac{rc}{q} \tag{19}$$

Transformatin Equations

Suppose (x,y,z), (a,b,c), (p,q,r) is the initial position of an arm in robot coordinates and (X,Y,Z), (A,B,C), (P,Q,R) is the final position of the arm.

If Axis 1 (workpiece pitch moves through an angle of α radians then

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

$$\begin{pmatrix} P \\ Q \\ R \end{pmatrix} = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} E(1-\cos\alpha) - F\sin\alpha - G \\ 0 \\ F(1-\cos\alpha) + E\sin\alpha \end{pmatrix}$$

where (E,O,F) = coordinates of the centre of rotation for axis 1 at the rigs zero position.

and G = mm/radian extension of axis 2 with axis 1

If Axis 2 extends by e mm then

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} -e \\ 0 \\ 0 \end{pmatrix}$$

If axis 3 or 4 extend by d mm then

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} 0 \\ dq \\ dr \end{pmatrix}$$

The rotations of axis five is specfied as a rotation of the whole coordinate system by an angle β. Whilst axes six and seven ar shown by a local rotation of γ.

Transformations from Space to Motor Coordinates. Given the initial and final positions in robot coordinate the movements by solving the following equations.

$$\begin{pmatrix} P \\ Q \\ R \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix}$$

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

$$\cos\gamma = Aa + Bb + Cc$$

$$\begin{pmatrix} P \\ Q \\ R \end{pmatrix} \sin\gamma = \begin{pmatrix} Bc - Cb \\ Ca - Ac \\ Ab - Ba \end{pmatrix}$$

and

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} -e \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ dQ \\ dR \end{pmatrix}$$

$$+ \begin{pmatrix} E(1-\cos\alpha) - F\sin\alpha - G \\ 0 \\ F(1-\cos\alpha) + E\sin\alpha \end{pmatrix}$$

APPENDIX C - PROGRAM SUITE USED FOR OFF-LINE DATA BASE GENERATION AND ON-LINE CONTROL

OFF-LINE

HEIGHT Output File.BND, File.ZHT

Automatically generates a 1 mm square grid of a component using the Coordinate Measuring Machine. The operator uses the CMM to define a rectangle enclosing the component, the datum for height data and the coordinates that mark the mounting points of the component (fig C.1). The program first generates the boundary of the component. Points that lie within the boundary are then probed along th lines of the grid, producing a fine incremetal slice of the component. The probing direction either horizontal or vertical is selected by the local curvature. Once the slice is created the radius of the probing ball is compensated for and the grid points are stored (fig C.2).

LATTICE Input File.BND
Output File.TNG

Given the boundary of the component it generates the initial mesh for the triangulation structure. The operator can select the link length of the mesh. Generating a mesh with a smaller size than that desired on completion of the triagulation ensures that the trianguation will obtain a solution quicker.

TRIANG Input File.TNG, File.ZHT
Output File.TNG, File.STA

Performs the successive iterations on the model to produce the ideal triangulated structure. The operator can control the size of the optimum links and the tolerances and actions performed upon out of spec. links. The process can be halted to display the current structure upon a graphics device or stored to disc.

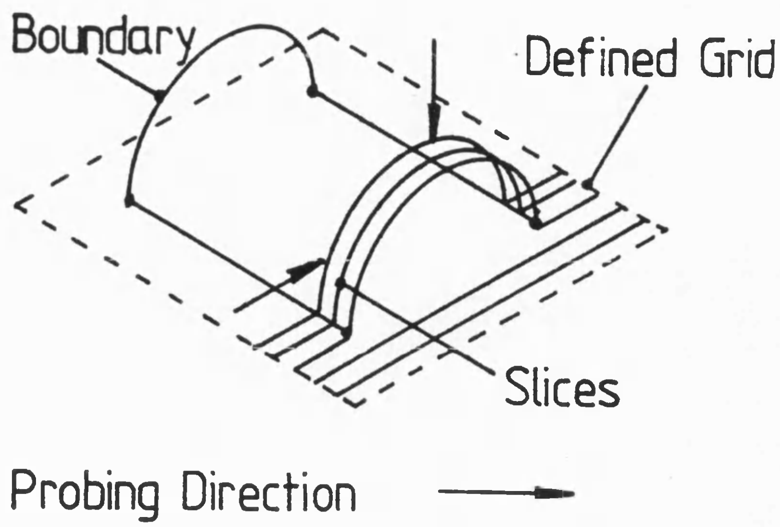

Figure C.1 Creation of Height Ordinate Data

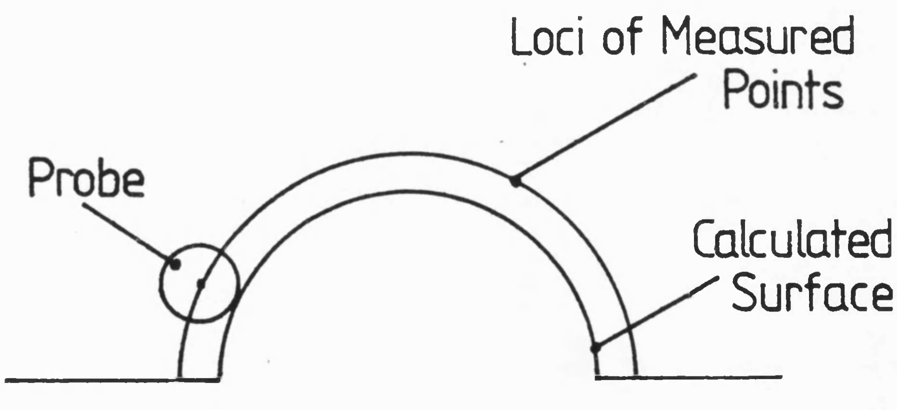

Figure C.2 Compensation for Probe Diameter

ODDJOB	Input	File.TNG
	Output	File.TRI, File.VER

Converts the node-link structure of the triangulated mesh into a list of triangles and vertices. The routine also mirrors components about the split line to generate a complete model.

CREVWS	Input	File.TRI, File.VER
	Output	File.GRP, File.LTV, File.LTT, File.ADJ File.TRI, File.STA

Creates the inspection groups.

POLPAT	Input	File.GRP, File.LTV, File.LTT, File.ADJ
	Output	File.GRP, File.POL, File.PGR, File.PAJ File.STA

Creates the polishing patches

SETGEN	Input	File.POL,File.GRP
	Output	File.GEN

Stores information on number of groups and patches and defines the size of the safe surface and the chuck.

SURFACE	Input	File.TRI, File.VER, File.GRP, File.POL File.PGR, File.PAJ, File.LTT, File.LTV File.GEN
	Output	File.SUR, File.BDG, File.PTH, File.PNT File.VWS, File.CVX, File.STA

Creates the surface, bridging, and safe surface points for machining and the camera inspection positions. They are then transformed from the cartesian coordinates to the robot coordinate system. Groups are marked as convex or concave.

POLINK	Input	File.SUR, File.PNT
	Output	File.LNK, File.STA

Creates the links within each polishing patch.

3DTO5D	Input	File.GEN, File.SUR, File.BDG, File.PTH
		File.VWS, File.PNT
	Output	File.MOT, File.ANG

Converts the points from the robot coordinate system into motor steps. It also calculates the rotation of the image with respect to the camera.

MASK	Input	File.GRP, File.LTV, File.VER, File.ANG
	Output	File.LSC

Creates the line scan masks for the individual groups.

ON-LINE

BOTTOM

Controls the movement and adaptive control of the robot on the bottom processor. The routine can be interupted by the operator to allow manual movement or inspection of the position or feedback registers. The system includes a number of basic routines for control of the different tasks.

'DRIVER' - Will step the axes specified by the motor and direction registers

'DDA' Calculates the relative movement of each axis and then performs the move with ramping of speed so that all motors start and stop at the same time.

'AIRMOT' Switches the airmotor on and off and activates the monitoring for stalling or belt brocken.

'FEEDBC' Enables and starts the vibration monitioring.

MIDDLE

Performs the local path planning and controls the inspection of the component. The processor is interfaced via a parallel link to the vision system, and serial links to the TOP processor. The processors memory is loaded with the encoded line scan masks and the polishing patch link data.

TOP

Controls the complete scurfing process while maintaining an up to date display of robot position and patch state information

DIAGNOSIC

A utility has been developed to enable the component data base to be examined and display results both graphically and in terms of cartesian or robot coordinates. The following information can be obtained.

1) Polishing Patch Construction - Displays the patch and lists all triangles, vertices, and inspection groups within the patch and displays the adjacent patches.
2) Polishing Patch Surface points - Lists all surface points in the three coordinate systems, and allows graphical display of the linking and allows the travelling salesman algorithm to b run.
3) Inspection Group Construction - Displays the group as a triangulated structure and as a line scan mask. Lists all triangles and vertices and neighbouring groups.

4) Single Triangle - Lists vertices and adjacent triangles
5) Single Vertex - Shows vertex coordinates and adjacent vertices.
6) Component Group Statistics - Displays data on groups and patches.
7) Component Statistics - Displays the number of patces and groups and the parameters selecte by the operator in creating the data base.
8) Graphically displays the triangulated component
9) Graphically displays the grouped and patched component

APPENDIX D - DATA BASE ORGANISATION

Each group or patch will have a different number of triangles, vertices or other information stored about it. If records are used to store the infomation then it will have to be set so that it can store the theoretical maximum for each group, resulting in a lot of wasted space both on disc and in memory. Instead two arrays are used to store the data. The first array has a single entry for each group that is an index into the second array. The data for each group is then stored contiguously in the second array starting at this point.

Group	1	2	3	4	5	6
Index	1	12	17	25	32	45

With the above index group 3 data starts at 17 and ends at 24 (As group 4 starts at 25). Therefore group 3 has 25-17, 8 elements. This data structure is referred to as the index/list form. Files that have a fixed ammount of information use fixed record sizes.

*.ADJ Index/list, contains lists of adjacent groups to each inspecion group.

*.ANG Fixed record, stored the rotation of the linescan mask due to rotation of the periscope.

*.BDG Index/list, index of bridging points to neighbouring patches in the *.PNT and *.MOT files. Uses an identical ordered index to that of the adjacent patches.

*.BND ASCII file, list of boundary points obtained for the CMM

*.CVX Index/list, states whether adjacent patches are convex or concave and whether the patch points were successfully conveted into robot steps.

*.GEN ASCII file, number of polishing patches and inspection

groups, size of safe surface and chuck offset.

*.GRP Fixed record, seven elements, XYZ coordinates of the centre of the group and its surface normal, and which patch the group is in.

*.LNK Index/list, link structure for each surface point within a patch.

*.LSC Index/list, encoded line scan masks for each group.

*.LTT Index/list, list of all triangles within a group.

*.LTV Index/list, ordered list of all vertices on a group boundary.

*.MOT Fixed record, seven element robot motor coordinates plus % of maximum speed and feedback limits.

*.OUT Files output from diagnostic program.

*.PAJ Index/list, Adjacent polishing patches.

*.PGR Index/list, List of groups within a patch

*.PNT Fixed record, XYZ coordinates and direction cosine of each surface, bridging, safe and viewing point, plus feedback data. Direct correspondance to *.MOT file.

*.POL Fixed record, six elements, XYZ coordinates and surface normal of each patch.

*.PTH Index/list, index of safe surface point for each patch in *.PNT file.

*.PVX Index/list, Ordered list of boundary vertices in each patch.

*.STA	Fixed record, stores parameters selected by operator in creating component database.
*.SUR	Index/list, index of surface points for each patch in *.PNT and *.MOT files.
*.TNG	Fixed record ASCII file, contains the lattice structure of the model and each nodes coordinates. Plus component boundary nodes are marked.
*.TRI	Fixed record, seven element are stored for every triangle, the three vertices, and the three adjacent triangles, plus which group it is in.
*.VER	Fixed record, six elements, the XYZ coordinates, and its surface normal.
*.VWS	Index/list, index of points on path to viewing poisition for each inspection group.
*.ZHT	Fixed record ASCII file, size of grid and 1mm grid points of height ordinate data.

APPENDIX E - STATISTICS OF TESTPIECES

BARREL

Length	80 mm.
Diameter (max)	80 mm.
Diameter (min)	63 mm.
Weight	0.5 kg.

Number of triangles	1266
Number of vertices	700
Number of inspection groups	114
Number of polishing patches (concave)	23
Number of polishing patches (convex)	0
Number of accessable patches	16
Transforms failed due to polishing	2
Transforms failed due to inspection	5
Transforms failed due to both	0
Number of surface points	445

Options selected

Ideal triangle size	5.0 mm.
Maximum angle for viewing group	12.0 deg.
Maximum radius for viewing group	10.2 mm.
Maximum angle for polishing patch	43.2 deg.
Maximum radius for polishing patch	14.0 mm.

Link sort crieria distance/angle

Minimum link angle	5.0 deg.
Maximum link angle	25.0 deg
Minimum links per node	3
Minimum links for centre node	4

TAP

Length	124 mm.
Diameter (max)	40 mm.
Diameter (min)	15 mm.
Weight	0.3 kg.

Number of triangles	1148
Number of vertices	646
Number of inspection groups	177
Number of polishing patches (total)	25
Number of polishing patches (concave)	17
Number of polishing patches (convex)	8
Number of accessable patches	7
Transforms failed due to polishing	3
Transforms failed due to inspection	13
Transforms failed due to both	2
Number of surface points	424

Options selected

Ideal triangle size	5.0 mm.
Maximum angle for viewing group	12.9 deg.
Maximum radius for viewing group	10.8 mm.
Maximum angle for polishing patch	34.0 deg.
Maximum radius for polishing patch	13.4 mm.

Link sort crieria distance/angle

Minimum link angle	4.0 deg.
Maximum link angle	30.0 deg
Minimum links per node	3
Minimum links for centre node	4